



# Impacts of landscape changes on local and regional climate: a systematic review

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Received: 10 August 2019 / Accepted: 16 April 2020 / Published online: 24 April 2020  
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## Abstract

**Context** Studies have shown that land use and land cover change (LUCC) has myriad impacts on local and regional climate. Synthesizing the recent findings in this field helps advance landscape ecology and sustainability science in the face of climate change.

**Objectives** To review and synthesize mesoscale modeling-based studies examining the impact of LUCC on climate, and to identify research gaps and future research directions.

**Methods** We adopted a systematic review procedure to identify and analyze relevant literature obtained from the Web of Science spanning Jan 1990–Nov 2018.

**Results** The number of publications per year increased from about 5 before 2008 to as large as 25 thereafter. About 60% of the case studies were focused on China and the US. Urbanization and agricultural development exerted a stronger influence on temperature than other LUCC modifications, with temperature changes generally between 1 and 2 °C. The climate effect of forest loss and urbanization

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illustrated location-dependency, as similar landscape changes in different latitudes showed climate effects of opposite sign. Extensive irrigation and dam construction increased precipitation, while the impact of urbanization and forest cover change on precipitation was inconclusive (positive, neutral, and negative).

**Conclusions** Understanding landscape and climate change interactions is essential for studying the ecology and sustainability of regional landscapes. Future research needs to: (1) understand climate effects resulting from land management change, (2) investigate climate change impacts on human health as induced or mediated by landscape changes, and (3) develop sustainable landscapes that can mitigate and adapt to climate change.

**Keywords** Systematic review · Landscape impacts on climate · Land–atmosphere interactions · Regional climate modeling

## Introduction

Land use activities, such as converting natural landscapes to crop fields and cities or changing land management practices across a region, have transformed a large proportion of the Earth's land surface, resulting in profound impacts on hydrology, soil, climate, biodiversity, and ecosystem processes (Lambin et al. 2003; Foley et al. 2005; Wu 2013a). The effects of land use and land cover change (LUCC) on climate have been widely acknowledged (Feddema et al. 2005; Gao et al. 2007; Mahmood et al. 2010; Pielke et al. 2011; Wang et al. 2014). LUCC affects climate through two general pathways: biogeochemical and biogeophysical (Feddema et al. 2005). The biogeochemical impacts of LUCC, i.e., the alterations of the chemical composition of the atmosphere and thus global climate, have been well documented and included in IPCC assessment reports (IPCC 2013). However, biogeophysical impacts of LUCC have received less attention (Pielke et al. 2011), although they may lead to local and regional climate change of similar, or even greater, magnitude as compared to greenhouse gas emissions (Sellers et al. 1997; Pitman et al. 2012; Georgescu et al. 2014). Through modification of land surface properties (e.g., vegetation fraction, leaf area index, albedo, emissivity, and

roughness), the biogeophysical pathway directly determines surface-absorbed solar energy and the ensuing transport of heat, moisture, and momentum between the land surface and the atmosphere, with additional consequences for temperature, air circulation, and precipitation changes (Pielke and Niyogi 2010).

Previous studies have indicated that local and regional climate can be highly sensitive to even small changes in land surface conditions (e.g., Chase et al. 1996; Pielke 2005; Georgescu et al. 2009a; Moore et al. 2010; Cao et al. 2015). Early research on this topic dates back to Charney (1975) who showed that increases of 14–35% in surface albedo reduced precipitation by about 40% during the rainy season in the Sahel region. This work highlighted the important contributions of LUCC on climate, and laid a foundation for subsequent research. Pielke and Avissar (1990) extended this research by demonstrating that small changes in landscape characteristics (i.e., vegetation and soil parameters) had pronounced effects on local and regional climate. Since then, the importance of landscape patterns to, for example, turbulent motions and mesoscale circulations in the planetary boundary layer has been increasingly recognized in climate change research (Raupach 1991; Weaver and Avissar 2001; Pielke and Niyogi 2010). Indeed, characterizing landscape and climate change interactions (i.e., understanding effects of changing landscape pattern on local and regional climate processes; landscape-based approaches to climate change mitigation and adaptation; landscape ecological studies of urban heat islands) has emerged as one of the top 10 research topics in the field of landscape ecology (Wu 2013b).

The atmospheric response to land surface modification can be examined by both observation-based analysis and model-based simulation. In situ observations provide local information, while satellite observations enable analysis across a larger spatial extent (Bonan 2001; Chapin et al. 2005; Ge 2010; Zhou et al. 2012; Peng et al. 2014; Li et al. 2015b; Bright et al. 2017). A key challenge associated with empirical data analysis is centered on the elimination of the influence of long-term climate fluctuations, although such concerns can be minimized through the use of the observation minus reanalysis approach (Kalnay and Cai 2003). Observation-based studies highlighted the significance of LUCC-induced climate change and

paved the way for model-based approaches to characterize the spatiotemporal patterns and underlying physical drivers. To simulate the impacts of LUCC on local and regional climate, numerical models are run to reproduce current climate conditions. Sensitivity experiments are subsequently performed to examine possible climate effects due to landscape changes. Given the advantages associated with improved process-based understanding, numerical models (e.g., the Weather Research and Forecasting Model) have been increasingly used in LUCC-climate change research, evidenced by the proliferation of publications during the past decade (Powers et al. 2017).

Although earlier research made great strides, the representation of realistic landscape patterns was largely restricted by the limitation of global circulation models and data availability to resolve spatial features at high resolution. Fortunately, this situation has been changing in recent decades with refinement of numerical models (e.g., limited area models of higher resolution that are applied over a region of interest) and development of remote sensing techniques. High-resolution satellite land surface products enable observations across a larger extent of the Earth's heterogeneous surfaces than is possible by ground survey alone, and have become an essential tool for monitoring land cover changes (Foody 2001). Indirectly, satellite data can facilitate detection of land use changes through, for example, hydrologic fingerprints (Rodell et al. 2009). Although global circulation models have long been applied to climate change research, the coarse spatial resolution (i.e., more than 100 km) utilized falls short of many key regional atmosphere and land surface processes (Brovkin et al. 2006). By contrast, mesoscale models, be they regional climate models or numerical weather prediction models, allow for more detailed process-based understanding and simulation of climate at regional scale (Rummukainen 2010). Such models are different from micrometeorological and turbulence resolving models, which are primarily used for short-term microscale research. In particular, the incorporation of satellite data into mesoscale models has facilitated more in-depth hydroclimatic understanding of land-atmosphere interactions.

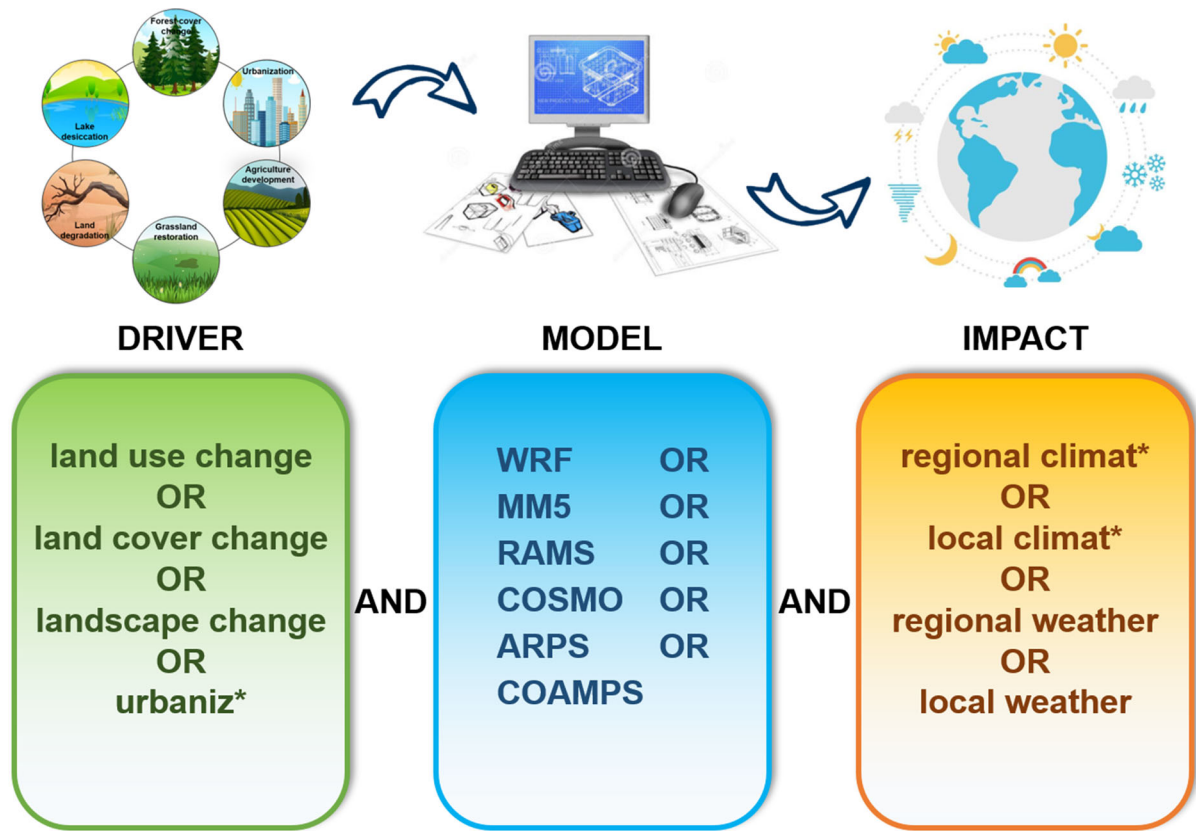
While much research progress has been made in the area of landscape impacts on climate using mesoscale models and satellite products, recent reviews and syntheses are lacking. Several authors have reviewed

landscape impacts on a specific climate element (e.g., Pielke et al. 2007) or climate effects due to changes in a particular land use/land cover type (e.g., Bonan 2008; Chapman et al. 2017). Pielke et al. (2011) and Mahmood et al. (2014) provided more recent reviews on the topic based on geographic regions and climate elements. Compared with the existing reviews, the main objectives of our review here were to (1) provide a more comprehensive and up-to-date assessment of LUCC impacts on local and regional climate, with a particular emphasis on mesoscale modeling studies and (2) identify knowledge gaps and future research directions. The literature covered in our review spans from January 1, 1990 and November 1, 2018, explicitly considering a range of land use activities (e.g., urbanization, forest cover change, agricultural development, grassland restoration and degradation, lake desiccation, and dam construction) and climate variables (e.g., air temperature, wind, humidity, and precipitation).

## Methods

We conducted a systematic review to synthesize impacts of landscape changes on local and regional climate. We focused on biogeophysical processes because a great deal of attention has been devoted to alterations of atmospheric composition and associated climate effects, while less attention has been paid to the direct influence of land surface modification on the climate system (Pielke et al. 2011). The systematic review required a detailed and comprehensive strategy prior to the execution of literature search, with the goal of reducing bias by identifying, appraising, and synthesizing all relevant research on a particular topic (Gurevitch et al. 2018). Because systematic reviews tend to have a higher degree of repeatability than traditional narrative reviews (Nunez-Mir et al. 2016), we adopted the systematic review procedure in searching relevant English articles published between January 1, 1990 and November 1, 2018 in the Web of Science (<https://apps.webofknowledge.com/>). The search words used are shown in Fig. 1.

A hierarchical search routine was used to assist literature retrieval (Fig. 1). First, three categories of search terms were established: “Driver”, “Model”, and “Impact”. Second, specific terms for each of three categories were assigned that were broad enough to



**Fig. 1** Search terms used in the literature retrieval. Three categories of search terms (i.e., “Driver”, “Model”, and “Impact”) were established first, with specific terms assigned to each category. The selected mesoscale models were the Weather Research and Forecasting Model (WRF), the

Mesoscale Model 5 (MM5), the Regional Atmospheric Modeling System (RAMS), the Consortium for Small-Scale Modeling (COSMO), the Advanced Regional Prediction System (ARPS), or the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS)

include relevant articles, while particular enough to restrict irrelevant ones. For the category “Driver”, we used “land use change” or “land cover change” or “landscape change” or “urbaniz\*”. For the category “Impact”, we chose “regional climat\*” or “local climat\*” or “regional weather” or “local weather”. We added “weather” to the literature search because more than a few relevant studies focused on extreme weather events or sub-seasonal simulations. That is, although we gave primary attention to climate, we did not preclude weather. Here, “local” referred to a very specific geographic area (e.g., city and metropolis) while “regional” referred to an area having definable characteristics but not always fixed boundaries (e.g., county, province, and ecoregion). Note that “regional” was not necessarily larger than “local” in different contexts.

For the category “Model”, we selected the widely used mesoscale modeling systems “the Weather Research and Forecasting (WRF) Model” or “the Mesoscale Model 5 (MM5)” or “the Regional Atmospheric Modeling System (RAMS)” or “the Consortium for Small-Scale Modeling (COSMO)” or “the Advanced Regional Prediction System (ARPS)” or “the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS)” as search terms. The WRF model is a next-generation mesoscale numerical weather prediction system designed for atmospheric, meteorological, and general climate research as well as operational forecasting applications; MM5 is the predecessor of WRF used for operational forecasting and meteorological, climatological, and general scientific applications; RAMS is designed primarily for mesoscale meteorological modeling applications; COSMO is a limited-area atmospheric prediction

model for both operational numerical weather prediction and various scientific applications; ARPS is a comprehensive regional to storm-scale atmospheric modeling and prediction system; COAMPS is a numerical model primarily used for wind nowcasts and forecasts.

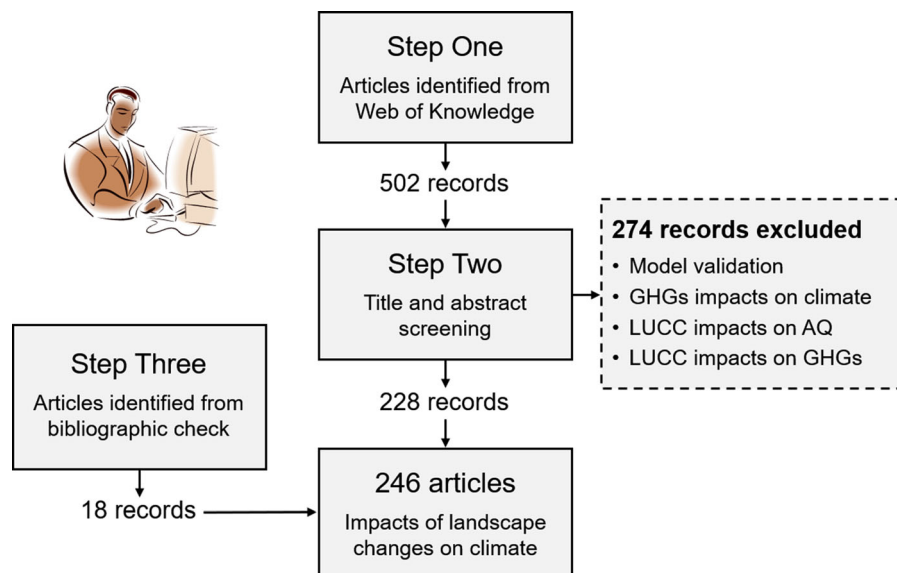
We conducted the literature search between November 10th, 2018 and November 17th, 2018, and a total number of 502 articles were retrieved in the initial round (Fig. 2). The subsequent title and abstract screening resulted in an inclusion of 228 articles and an exclusion of 274 articles. The 274 articles were excluded because they merely targeted one of the following topics with no additional focus on the biogeophysical impacts of LUCC on climate: (1) model validation (156 articles), (2) climate change due to greenhouse gas emissions (72 articles), (3) the effect of LUCC on air quality (43 articles), and (4) the effect of LUCC on atmospheric composition (3 articles). While these four topics are critically important in advancing scientific understanding, they were not the central focus of our work. In addition to the 228 articles retained, 18 extra relevant articles were identified via bibliographic checks, thus yielding a final sample of 246 articles. The 246 articles consisted of 240 research articles, 5 review articles, and 1 book chapter (entitled “Benefits of urban green space for

improving urban climate”). Our focus was on the synthesis of the 240 research articles.

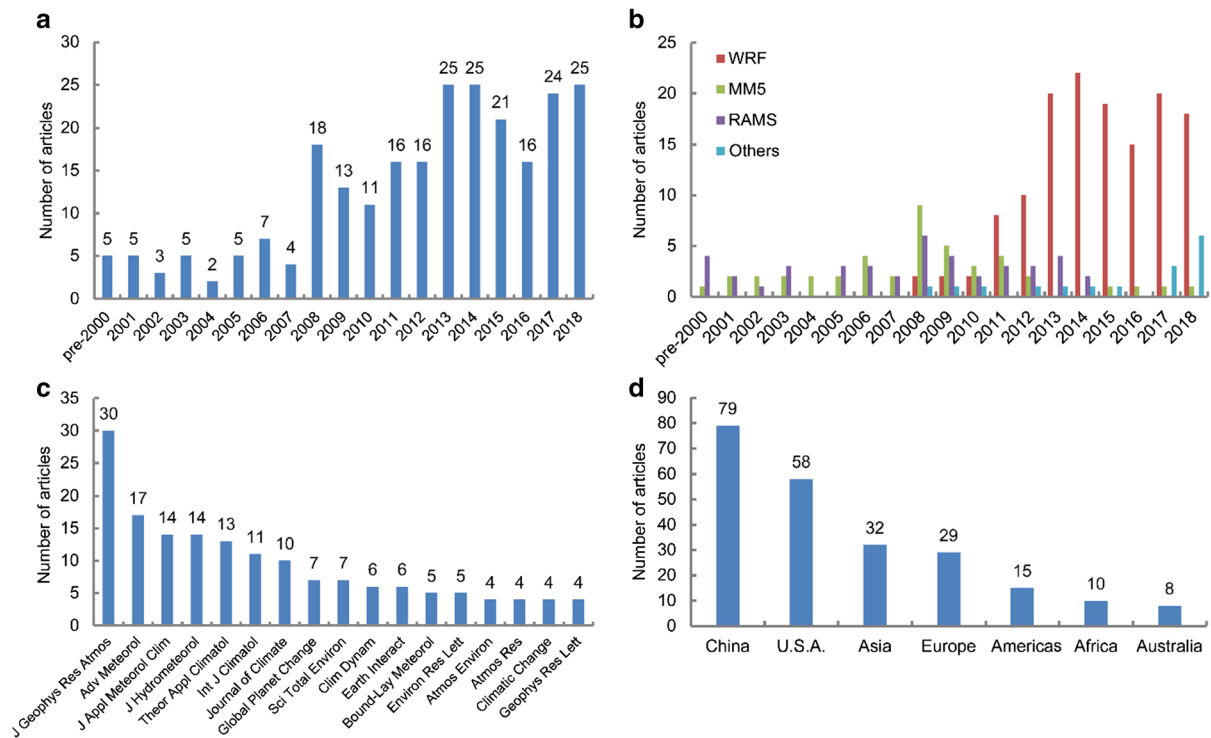
## Results

### General characteristics of the literature reviewed

In terms of the number of articles published per year during 1990–2018 (Fig. 3a), the year of 2008 was a turning point, marking the beginning of a heightened level of attention to the research topic. This was closely related to the increasing application of WRF (which is an open-source community model), or its predecessor, MM5 (Fig. 3b). According to Powers et al. (2017), WRF registrations displayed a sharp increase from 1000 registrations in 2006 to as many as 3000 registrations in 2008. Although the following economic crisis affected the distribution of WRF due to the computational cost, the number of registered WRF users increased again after 2010 (Powers et al. 2017). This was generally consistent with the number of WRF-related publications per year. Note that MM5 and RAMS were the primary research tools used for numerical simulations before the high-resolution mesoscale model of greatest use, i.e., WRF, became a major research tool. The 240 articles were published in 67 journals, with 161 articles (~ 67% of the total)



**Fig. 2** Flowchart showing the number of articles identified at each stage of the review process (AQ-air quality; GHGs-greenhouse gases; LUCC-land use/land cover change)



**Fig. 3** Synthesis of retrieved articles published during January 1st, 1990–November 1st, 2018: **a** the number of articles published per year, **b** the number of articles with utility of WRF, MM5, RAMS, or other models (i.e., COSMO, COAMPS, or ARPS), **c** the number of articles published in 17 out of 67 journals (i.e., only journals that published no less than 4 articles

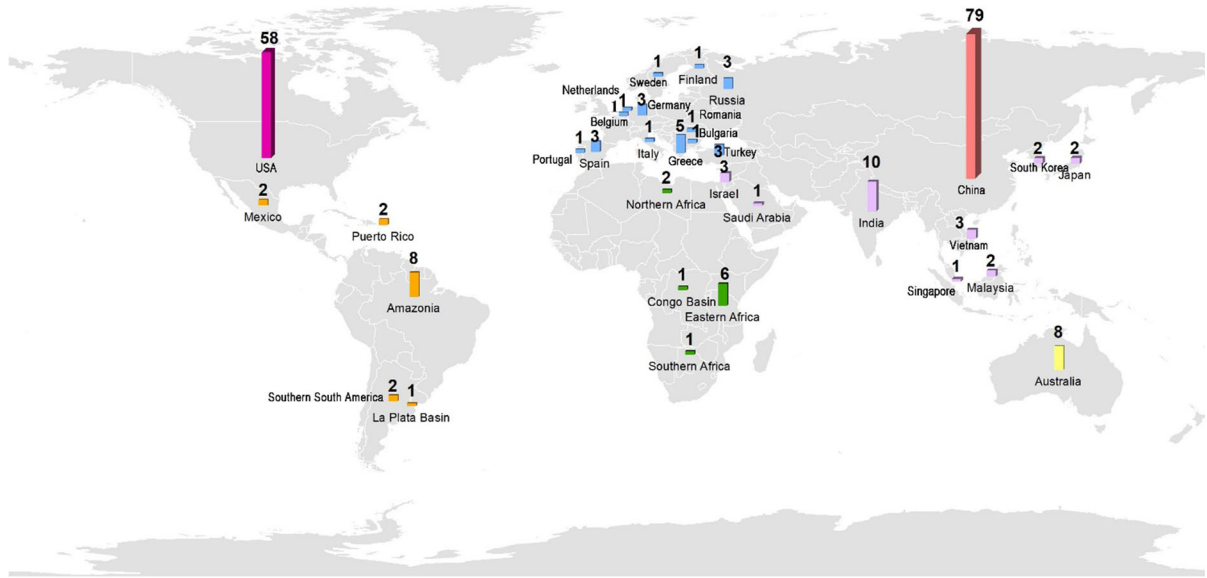
are listed), and **d** the number of case studies on China, USA, Asia (excluding China), Europe, Americas (including North, Central, and South America but excluding USA), Africa, and Australia. The number of articles in (**d**) equals 231 because 9 out of the 240 research articles have no specific case study area

published in 17 journals (Fig. 3c). Among these journals, *Journal of Geophysical Research: Atmospheres* (30 articles), *Advances in Meteorology* (17 articles), *Journal of Applied Meteorology and Climatology* (14 articles), *Journal of Hydrometeorology* (14 articles), *Theoretical and Applied Climatology* (13 articles), *International Journal of Climatology* (11 articles), and *Journal of Climate* (10 articles) ranked as the top seven journals that published no less than 10 research articles during our search period.

The 240 research articles reported 231 case studies altogether, including 79 cases in China, 58 in the US, 32 in Asia (excluding China), 29 in Europe, 15 in the Americas (including North, Central, and South America but excluding the US), 10 in Africa, and 8 in Australia (Fig. 3d). A more detailed illustration of the locations of these case studies is shown in Fig. 4. For the 79 cases in China, 8 cases were focused on the entire continental China, 56 cases on regional geographies (e.g., the Pearl River Delta, Yangtze River Delta,

Guizhou Karst Plateau, and Hetao Plain), 12 cases on individual cities (e.g., Beijing, Suzhou, Wuhan, and Hangzhou), and 3 cases detailing lakes and dam impacts (e.g., the Three Gorges Dam, Lake Nam Co, Lake Ngoring, and Lake Gyaring). For the 58 cases in the US, 6 cases were conducted over the continental US, 34 cases focused on regional geographies (e.g., the Great Plains, High Plains, and Central Grasslands), 14 cases were concerned with particular urban environments (e.g., Phoenix, Los Angeles, Las Vegas, and Philadelphia), and 4 cases were designed for the examination of dam impacts (e.g., the Folsom Dam and Owyhee Dam). For Asia (recall that we exclude China), 12 cases were centered on India, while the remaining 20 cases were spread over the entire region. For Europe, 4 cases were carried out for continental Europe, while 25 cases dealt with individual countries or cities (e.g., Athens, Iberian Peninsula, Turkey, and Moscow). For the Americas (recall that we exclude the US), 8 out of 15 cases were carried out in Amazonia,





**Fig. 4** Geographic distribution of the case studies. The illustration is aggregated across countries or regions (e.g., Amazonia and Eastern Africa), with the number of studies for

each case shown on bars. The bar colors represent the continents where the case studies are located, with China and the US shown separately

while 2 cases each targeted Mexico and Puerto Rico, respectively.

Examples of LUCC included urbanization, forest cover change, agricultural development, grassland restoration and degradation, lake desiccation, and dam construction, with the number of studies for each topic presented in Table 1. We next synthesized how different types of LUCC influence local and regional climate, including both the magnitude and direction of the climate effects. Typically, landscape changes, through modification of land surface biophysical properties like surface albedo, emissivity, roughness, leaf area index, stomatal resistance, and root depth, directly determine the energy, moisture, and

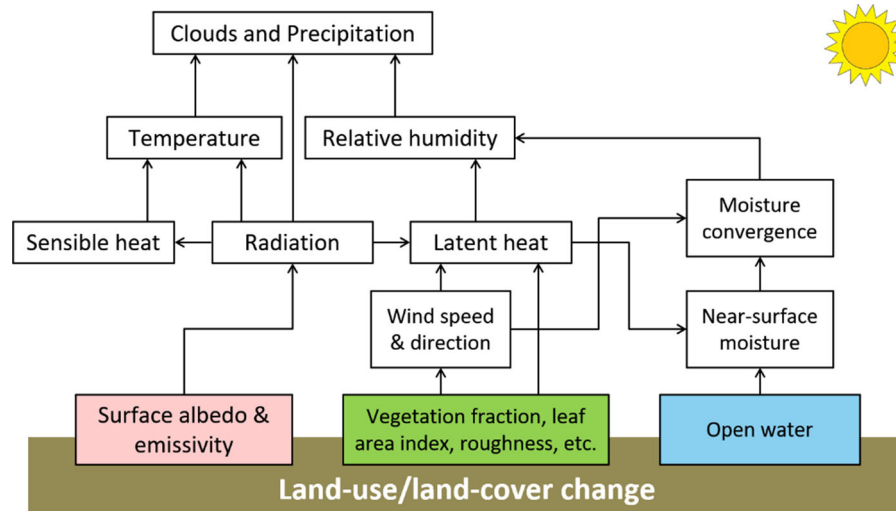
momentum exchange between the land surface and overlying atmosphere, thus exerting strong influence on temperature, air circulation, and rainfall (Fig. 5). In certain cases, landscape changes may affect the land-sea breeze in coastal zones and mountain-valley breeze in mountainous areas; the changes may also have an effect on the monsoon circulation.

#### Impacts of urbanization on climate

Urbanization is an extreme case of human modification of the Earth’s terrestrial surfaces, and has been recognized to be a highly significant driver of climate change at local and regional scales (Mills 2007). According to Liu et al. (2018b), global urban extent increased by 65% (i.e., about 300,000 km<sup>2</sup>) from 1990 to 2010. During this period of time, China, the US, and India accounted for nearly 43% of the world’s total urban expansion (Liu et al. 2018b). Although urban areas only occupy a relatively small portion of our planet’s land territory, they are home to more than half of the world’s population and generate more than 70% of global energy use and energy-related emissions (Seto et al. 2017). Therefore, understanding the role of urbanization on climate has received considerable attention in the scientific community (Grimm et al. 2008; Seto and Shepherd 2009; Buyantuyev and Wu

**Table 1** The number of studies for each type of land use/land cover change

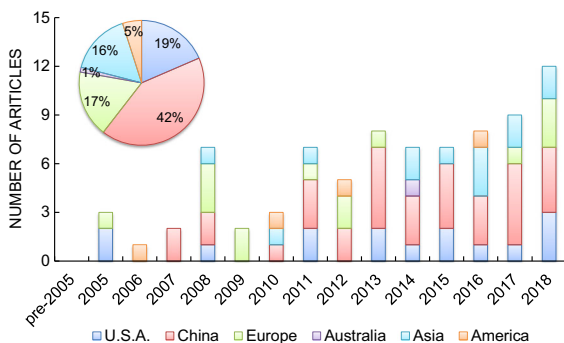
Land use/land cover change	# of papers
Urbanization	81
Forest cover change	26
Agricultural development	22
Grassland restoration and degradation	8
Lake desiccation and dam construction	11
Multiple LUCC	92



**Fig. 5** Pathway showing the biogeophysical impact of land use and land cover change on local and regional climate (revised from Mölders 2011)

2010; Ma et al. 2016). For a non-desert environment, urban expansion decreases vegetation fraction owing to the contiguous increase in impervious surfaces. Together with high heat-storage capacity and impediments to atmospheric motion from the development of 3-d urban infrastructure, the surface energy budget, hydrological cycling, and structure of the planetary boundary layer are modified accordingly, thus leading to changes in climate elements.

Recently, mesoscale modeling work has been increasingly emerged to investigate impacts of urban expansion on climate in major metropolitan regions around the world (Fig. 6). A majority of these studies



**Fig. 6** Histogram showing the number of articles published per year that examined the impact of urbanization on climate during the search period (i.e., 1990–2018). Different colors in a bar represent the location of case studies. The percentage in the pie is the proportion of articles on a particular region to the total number of articles published during 2005–2018

paid close attention to urbanization impacts in the US, China, Europe, and the rest of Asia (especially India), while comparatively few studies were conducted in the rest of America (especially South America), Africa, and other parts of the world. The most widely manifested urbanization-induced climate change is the urban heat island effect (UHI; Oke et al. 1991). In addition to the physical expansion of urban lands, anthropogenic heat emission, either from the heating-ventilation-air-conditioning system or the transportation system, resulted in further air temperature increases in built-up areas (Sailor and Lu 2004). For example, urbanization and associated anthropogenic heat release were responsible for 70% and 30% of the UHI effect, respectively, in Hangzhou city, China during a heatwave event (Chen et al. 2014). In contrast with the number of research examining the effect of urban land expansion, only nine papers with explicit consideration of anthropogenic heating were identified in our review (i.e., Dandou et al. 2005; Fan and Sailor 2005; Lin et al. 2008a; Feng et al. 2012, 2015; Chen et al. 2014; Wang et al. 2015; Benson-Lira et al. 2016; Chen and Frauenfeld 2016). Generally, the contribution of anthropogenic heating to UHIs (i.e., 10–30%) was smaller than that of urban land expansion in summer, while the reverse was true in winter.

However, urban land expansion in arid and semi-arid desert regions has been shown to cause urban cool islands during the daytime (e.g., about  $-1\text{ }^{\circ}\text{C}$  in



Phoenix and  $-0.5$  to  $0$  °C in Las Vegas) and was responsible for the development of classical UHIs during the nighttime (e.g.,  $1-3$  °C in Phoenix and Las Vegas; Georgescu et al. 2009b, 2011; Kamal et al. 2015; Kaplan et al. 2017). This was because urban land expansion decreased sensible heat flux in the daytime owing to increased energy storage relative to the prior land use/land cover (Georgescu et al. 2011). This highlights the importance of local background climate and geography on the UHI intensity (Zhao et al. 2014). In addition to the urban–rural air temperature difference, urban expansion in coastal zones increased air temperature gradients between the urban area and nearby ocean, thus enhancing land-sea breezes (Lo et al. 2007; Lin et al. 2008a; Lu et al. 2010; Li et al. 2015a; Miao et al. 2015; Wang et al. 2015) and even the monsoon circulation (Feng et al. 2015). For example, Feng et al. (2015) argued that urbanization in China strengthened southerly winds over East Asia, and as a result, the monsoon circulation was intensified in summer (i.e., the prevailing southerly winds were amplified).

Although urbanization impacts on air temperature were well documented, impacts on rainfall were less clear: positive (Lei et al. 2008; Feng et al. 2012; Zhan et al. 2013; Kusaka et al. 2014; Benson-Lira et al. 2016), neutral (Sertel et al. 2011; Ke et al. 2013), and negative (Trusilova et al. 2009; Wang et al. 2012). On the one hand, urban expansion enhanced rising motion locally, destabilized the atmosphere, and perturbed thermodynamic processes with increased surface roughness and drag, which were favorable for the generation of extreme rainfall and thunderstorms (Lin et al. 2008b; Mahmood et al. 2010; Niyogi et al. 2011; Schmid and Niyogi 2013; Zhang et al. 2014; Shi et al. 2017). On the other hand, continuous expansion of built environments (e.g., urban agglomerations) reduced low-level atmospheric moisture content and thus convective available potential energy, which played a negative role in the formation of rainfall (Pielke and Niyogi 2010; Feng et al. 2015). Numerical simulations were also designed to examine how urban landscape patterns affected rainfall by improved process-driven understanding. For example, dispersed urban landscapes with large extent and low density tended to increase the rainfall amount, while compact urban landscapes modified rainfall toward higher intensity and lower frequency of occurrence (Goswami et al. 2010; Ke et al. 2013). Miao et al. (2011)

showed that urbanization prior to 1980 reduced maximum rainfall in Beijing, while subsequent urbanization facilitated the development of convection with increased maximum and accumulated rainfall.

Apart from the examination of urbanization impacts, the effect of adaptation strategies (e.g., cool, green, and photovoltaic roofs) has also been examined using mesoscale models, so as to alleviate urbanization-induced weather and climate extremes (Synnefa et al. 2008; Georgescu et al. 2012, 2013, 2014; Vlachogiannis et al. 2012; Georgescu 2015; Sharma et al. 2016; Song et al. 2018; Liu et al. 2018a). For example, the installation of cool roofs (or highly reflective roofs) reduced surface-absorbed solar energy and lowered near-surface temperature by  $\sim 2$  °C in Arizona, USA and Athens, Greece (Synnefa et al. 2008; Georgescu et al. 2013). However, large-scale deployment of this kind of roof may aggravate moisture deficits, thus contributing to the reduction of summer rainfall by  $1-4$  mm/day in the southeastern US (Georgescu et al. 2014). Green roofs (or highly transpiring roofs) decreased urban temperature by a smaller magnitude than cool roofs (e.g., by  $1.2$  °C in Mexico City; Vázquez Morales et al. 2016), while the effect of green roofs on rainfall had large uncertainty (Georgescu et al. 2014). Unlike cool roofs, the deployment of photovoltaic panels on building roofs was shown to lower surface air temperature through the conversion of absorbed solar energy to electrical energy for use in building structures (Vlachogiannis et al. 2012). In addition to roof materials, the presence of urban parks, irrigated lawns, and vegetated roadsides was also shown to reduce urban temperature, via the partitioning of available energy into greater latent as opposed to sensible heat flux while enhancing the local hydrological cycle (e.g., oasis effect; Papangelis et al. 2012; Vahmani and Hogue 2015; Yang and Wang 2014; Yang et al. 2016).

#### Impacts of forest cover change on climate

Forests cover about  $42$  million  $\text{km}^2$  in tropical, temperate, and boreal lands (i.e.,  $\sim 30\%$  of the Earth's terrestrial surfaces; Bonan 2008). Human activities, primarily for crop production and timber extraction, have caused a loss of  $7-11$  million  $\text{km}^2$  of forests during the past 300 years, especially in the tropics (Foley et al. 2005). Such large-scale removal of natural forests and its subsequent impacts on climate

have raised great concerns in the scientific community (Bonan et al. 1992; Snyder et al. 2004; Davin and de Noblet-Ducoudré 2010). Previous research has indicated that forest loss resulted in drier environments, reduced cloud fraction, and enhanced winds owing to decreased evapotranspiration and surface roughness (Bonan 2008). However, the impact of forest loss on air temperature was largely subject to latitude, another typical example of location-dependent climate response to similar landscape changes. Concretely, forest removal has been shown to cause cooling in high-latitude regions because of increased surface albedo, while warming was expected to be of greater importance in low-latitude regions as a result of reduced evapotranspiration (Snyder et al. 2004). In other words, background climate conditions largely determined the biogeophysical effect of forest cover change.

Specifically, across low-latitude regions of the world, eleven studies retrieved on forest loss have shown that the warming effect of reduced evapotranspiration largely offset the cooling effect of increased surface albedo, thus resulting in net warming (Table 2). A majority of these studies (i.e., 7 out of 11) were conducted in Amazonia, while the remaining four studies were carried out in Mount Kilimanjaro, the Congo Basin of Central Africa, the Borneo Island of Malaysia, and Southeast Asia. Different from low-latitude regions, the cooling effect became dominant

in the absence of boreal forests in high-latitude regions. The relatively weak warming effect arising from the reduction of evapotranspiration of needleleaf forests cannot offset the strong cooling effect due to the increase in surface albedo, especially in winter. Therefore, cooling effects of forest loss were found in high-latitude regions. Aside from air temperature, the loss of forests in the tropics reduced the amount of rainfall and enhanced the amplitude of drought. However, these effects were modulated over high-altitude regions (e.g., > 2000 m). This was because the decrease in aerodynamic resistance strengthened wind speed and convergence (i.e., the horizontal inflow of air), causing air to rise that eventually led to the formation of clouds and precipitation (Fairman et al. 2011). A heterogeneous deforestation (e.g., “fishbone” deforestation) has also been shown to increase cloud fraction and precipitation under weak synoptic-scale forcing (Roy 2009). The establishment of a horizontal temperature gradient forced cool, moist air from adjacent forests to converge over the bare patches, and the convergence created strong updrafts, shallow cumulus clouds, and rainfall, which were primarily located over the clearings (Roy 2009). Regarding forest expansion, only one case study focused on northern Europe was identified here.

Similar research has also been conducted in mid-latitude regions (i.e., China, the US, and Europe), where considerable broadleaf forests were cleared for

**Table 2** Locations of studies that examined the impact of forest cover change on climate in low- and high-latitude regions

Authors (years)	Location	$\Delta$ temperature
Forest loss in low latitudes		
Roy and Avissar (2002), Roy (2009)	Amazon Rainforest, Brazil	> 0.4 °C in JJA
da Silva and Avissar (2006), da Silva et al. (2008)	Amazon Basin	0.3 °C in JF
Fairman et al. (2011)	Mount Kilimanjaro	Warmer in July
Zhang et al. (2013b)	Amazon Basin, Brazil	< 1 °C in JJA; 1–2 °C in DJF
Bagley et al. (2014)	Amazon Basin	0.32 °C in JJAS
Akkermans et al. (2014)	Congo Basin	0.65 °C annual average
Tolle et al. (2017)	Southeast Asia	< 2 °C in NDJFM
Forest loss in high latitudes		
Li et al. (2013b)	European Russia	– 0.58 °C annual average
Cherubini et al. (2018)	Europe	> – 1 °C annual average
Rydsaa et al. (2015)	Northern Europe	0.2 °C annual average
Cherubini et al. (2018)	Europe	< 0.9 °C annual average

JJAS from June to September, NDJFM from November to March

agricultural use (Table 3). However, the impact of forest loss on air temperature in the broad mid-latitude regions was not conclusive, and was responsible for both warming and cooling effects, dependent on the dominant biogeophysical process that drove such changes. For example, forest loss in mid-latitude Europe had no impact on summer temperature, while winter temperature decreased by 1.5 °C due to this type of terrestrial modification (Vanden Broucke et al. 2015). On the contrary, in the northeast of China, forest loss reduced summer temperature by 0.5 °C, while changes in winter temperature were negligible (Wang et al. 2015). Although the US and China are located at similar latitudes, the removal of forests in the northeastern US lowered air temperature by 2 °C in winter, while both warming and cooling were simulated in summer (Klingaman et al. 2008; Wichansky et al. 2008; Garcia et al. 2014; Burakowski et al. 2016). Forest expansion in mid-latitude regions (e.g., China, the US, and Europe) has received more attention than that in low- and high-latitude regions.

#### Impacts of agricultural development on climate

Croplands occupy about 15 million km<sup>2</sup> of the Earth's ice-free land (Ramankutty et al. 2008). That is, ~ 12% of the planet's natural vegetation has been cleared for cropland expansion, so as to support the growing population. In addition, the Green Revolution, including irrigation, chemical fertilizers and pesticides, high-yielding cultivars, and

mechanization, has also made a significant contribution to the increase in crop production (Foley et al. 2005). Recent research has demonstrated that both land cover and land management changes can affect mesoscale climate (Luyssaert et al. 2014; Bright et al. 2017; Cao et al. 2018a). The conversion of natural vegetation to cultivated lands increased surface albedo and reduced surface-absorbed solar energy, which lowered near-surface temperature. The decrease in latent heat flux further resulted in the reduction of low-level atmospheric moisture content. Therefore, cropland expansion, alone and separate from management practices, may have considerable cooling and drying effects (Pessacg and Solman 2012; Zhang et al. 2012). Bonan (1997) reported that cropland expansion in the central US reduced surface air temperature by ~ 2 °C in summer, and there was a significant linear relationship between expanded cropland areas and reduced daily maximum temperature (Bonan 2001).

In addition to the expansion of croplands, changing land use practices, particularly irrigation, also produce substantial climate effects. The increase in soil moisture as a result of irrigation enhanced evapotranspiration, increased latent heat flux, and reduced near-surface temperature by 1–2 °C in India, where irrigated agriculture has been a key component of poverty alleviation and economic growth (Douglas et al. 2009; Qu et al. 2013). The reduced surface air temperature can even offset the warming effect caused by nearby urbanization (Jin and Miller 2011). Meanwhile, agricultural irrigation increased precipitation

**Table 3** Locations of studies that examined the impact of forest cover change on climate in mid-latitude regions

Authors (years)	Location	Summer temp	Winter temp
Forest loss in mid latitudes			
Klingaman et al. (2008)	Mid-Atlantic, USA	↑	–
Wiedinmyer et al. (2012)	Colorado, USA	↑	×
Garcia et al. (2014)	Great Lakes states, USA	×	↓
Zheng et al. (2009)	China	↑	↓
Wang et al. (2015)	Northeastern China	↓	↑
Vanden Broucke et al. (2015)	Europe	–	↓
Forest expansion in mid latitudes			
Wichansky et al. (2008)	New Jersey, USA	↓	×
Burakowski et al. (2016)	New England, USA	↑	↑
Wang and Zhou (2003)	North China	–	×
Yu et al. (2013b)	Southeastern China	↓	↑
Yu et al. (2016)	Northwestern China	×	↓
Cherubini et al. (2018)	Europe	–	↑

↑ Warming, ↓ Cooling, – no significant impact, × not shown

by 25–175% through the addition of atmospheric moisture and the enhancement of the hydrological cycle (Perlin and Alpert 2001; Ter Maat et al. 2006; Sen Roy et al. 2011). Irrigation has also been shown to modify the land-sea breeze (Ter Maat et al. 2006) and even the monsoon circulation (Douglas et al. 2009). For example, extensive agricultural irrigation across India largely increased the regional moisture flux and thus convective available potential energy. The highly modified terrestrial water vapor flows around the Indian Ocean (i.e., a key component of the Asian monsoon system) further altered the monsoon circulation and associated monsoon rains.

#### Impacts of grassland restoration and degradation on climate

Grasslands cover about 28 million km<sup>2</sup> (i.e., ~ 22%) of the Earth's ice-free land (Ramankutty et al. 2008). Although grasslands around the world are essential to the survival of natural species and to the support of human life, grasslands are vulnerable to human disturbance. On the one hand, land degradation has caused severe negative ecological outcomes including the reduction of biodiversity, soil productivity, and water conservation capacity. On the other hand, grassland restoration is actively ongoing. Our literature review indicates that grasslands affect climate through two major pathways: (1) the restoration of grasslands from bare soil, and (2) the replacement of forests for grasslands. Grassland restoration reduced evaporation from bare soil and increased water content available to plants for transpiration, which lowered daytime maximum temperature by 1.2 °C during the growing season in the central US (Eastman et al. 2001) and reduced summer temperature by 1.5–3 °C in central China (Yu et al. 2013a). On the contrary, decreases in surface roughness and leaf area index due to the conversion of forests to grasslands reduced turbulent kinetic energy and latent heat flux, leading to January warming of around 1 °C in southeastern and southwestern Australia (Narisma and Pitman 2003) and annual warming of 0.6 °C in the Brazilian Amazon (Zhang et al. 2013b). These aforementioned biophysical changes were shown to reduce the formation of clouds and inhibit precipitation (Narisma and Pitman 2003).

Land degradation is defined as the temporary or permanent decline in the productive capacity of the

land (Conacher and Conacher 1995). Land degradation often results from, e.g., overgrazing (Ma et al. 2014), desertification (Gao et al. 2013), and fires (Hernandez et al. 2015). Natural hazards are excluded as a cause; however, human activities can indirectly influence the severity of phenomena such as floods and fires. Previous research has shown that grassland degradation in the Mongolian Plateau increased summer temperature in by 0.4–1.2 °C while reducing summer precipitation by 4–20 mm (Li et al. 2013a; Zhang et al. 2013a; Ma et al. 2014). Rocky desertification in the Guizhou Karst Plateau, which is located in southwestern China, increased precipitation over southeastern China (Gao et al. 2013). Across southwest regions of western Australia, the conversion of wooded grasslands to bare soil led to higher surface winds due to reduced roughness length, which resulted in enhanced moisture advection from the ocean to inland (Kala et al. 2010). Similarly, fire-burnt areas in Portugal produced intense frontogenesis with vertical velocity reaching a few meters per second, and this powerful meso-scale circulation pumped more humid air from the surroundings not affected by the wildfire, thus increasing cloudiness over the burnt areas (Hernandez et al. 2015).

#### Impacts of lake desiccation and dam construction on climate

We have identified 10 articles published during 2012–2017 that were focused on the impact of lake desiccation and dam construction on local and regional climate. For example, the decrease in lake surface areas of the Aral Sea in Central Asia resulted in significant warming of no less than 6 °C in summer because water bodies have much higher heat storage capacity than the land surface (Roy et al. 2014; Rubinshtein et al. 2014). Furthermore, the existence of lakes increased precipitation in the surrounding areas, especially in summer when the warm lake surface enhanced low-level horizontal convergence and updrafts, which contributed to the development of convective precipitation (Wen et al. 2015). Numerical simulations that were performed over Lake Nam Co of the Tibetan Plateau also indicated that the existence of the Lake enhanced mountain-valley breezes in the north slope of the Nyainqêntanglha Range in July, which contributed to convective cloud formation and

frequent precipitation across the north slope (Yang et al. 2015).

Aside from the lake impact on water bodies, dam construction, especially tall dams (i.e., higher than 15 m), has been shown to affect the climate system. It was estimated that there were more than 57,000 tall dams worldwide, with China having over 23,000 tall dams and the US some 9200. Tall dam construction in the US (i.e., the Folsom Dam and Owyhee Dam) led to a trivial cooling effect (i.e., 0.15 °C) in winter (Woldemichael et al. 2014a). Despite limited thermal impacts, the increase in the amount of atmospheric water vapor and enhanced vertical motion were responsible for the transport of moisture from the land surface to overlying atmosphere, which in turn, increased rainfall of varied intensity (Woldemichael et al. 2012, 2014b). For example, dam-triggered land use/land cover change led to an increase of 3–5% in the 72-h total rainfall around the Folsom Dam (located in the windward side), while an increase of 8% in the 72-h total rainfall was simulated around the Owyhee Dam (located in the leeward side). Increased rainfall (by 0–20% within 100 km around the reservoir area) was also detected in the Three Gorges Dam, China (Wu et al. 2006).

## Discussion

### Impacts of landscape changes on climate

Our literature review indicates that landscape changes may have various but important impacts on local and regional climate, and that these landscape impacts on climate were usually location-dependent (e.g., similar landscape changes led to different climate effects in different places). The greatest change in air temperature (i.e., as high as 6 °C) was caused by the desiccation of the Aral Sea in Central Asia. This was not only because the large thermal difference between water and land, but also the substantial decrease in the lake's surface areas (i.e., from 68,000 km<sup>2</sup> in 1960 to merely 8740 km<sup>2</sup> in 2010). In addition, urbanization and agricultural development were found to exert a stronger influence on air temperature than other LUCC types. Furthermore, our review highlights that extensive irrigation and tall dam construction increased precipitation owing to the addition of atmospheric water vapor and the enhancement of the hydrological

cycle, whereas the impact of urbanization and forest cover change on precipitation were inconclusive (i.e., positive, neutral, and negative).

The background climate, circulation feedback, and surrounding landscapes played an important role in determining the magnitude and even the direction of these climate effects (Table 4). The most pronounced location-dependent climate effects of landscape changes were found in the case of forest cover change. Although the impact of forest reduction in mid-latitude regions was not conclusive, the full range of simulated temperature differences, as revealed by the literature, was – 2.0 to 0.5 °C, indicating that the cooling effect arising from decreased surface albedo may be dominant. Another example exhibiting this location-dependent characteristic was the UHI effect. When investigating warming of urban expansion by latitudes (whether northern or southern latitudes), we found that the magnitude of daytime UHIs between 20° and 40° (i.e., 0.5–2.0 °C) was larger than that below 20° or above 40° (i.e., 0.2–0.6 °C). Apart from the synoptic-scale forcing, the regions between 20° and 40° (where Europe, China, India, and the US are located) accounted for a large proportion of the world's total urban expansion. Urbanization in desert regions could cause urban cool islands rather than classical UHIs during the daytime, a phenomenon which has been corroborated with satellite-based (Lazzarini et al. 2015) and direct observations (Brazel et al. 2000). Although we did not find this location-dependent characteristic for other LUCC types in this review, future work may fill the gap by retrieving sufficient research articles for a particular topic.

Our literature search did not include teleconnection effects because of the local and regional focus. However, long-distance climate effects induced by landscape changes can be important, and should be considered in land–atmosphere modeling (Lawton et al. 2001; Werth and Avissar 2002; Schneck and Mosbrugger 2011; Silva et al. 2016; Devaraju et al. 2018). For example, Silva et al. (2016) found that Amazon deforestation increased precipitation by 10% over the eastern South America and the adjacent South Atlantic Ocean, associated with intensification of upper-level high pressure (the Bolivian high) and negative geopotential height anomalies southeastward of the center of the high. Undoubtedly, advances in mesoscale models that involve a broader range of land surface processes (e.g., ecological, physiological, and



**Table 4** The location-dependent characteristic of landscape impacts on climate

Landscape change	Location	$\Delta$ temperature ( $^{\circ}\text{C}$ )
Urbanization in non-desert regions	Latitude $\approx 55^{\circ}$	0.20 to 0.60
	Latitude $\approx 40^{\circ}$	0.77 to 1.33
	Latitude $\approx 30^{\circ}$	0.50 to 2.00
	Latitude $\approx 20^{\circ}$	0.50 to 1.50
	Latitude $\approx 10^{\circ}$	0.30 to 0.60
Urbanization in desert	Latitude $\approx 35^{\circ}$	– 0.00 to – 1.30
Forest loss	Latitude $< 30^{\circ}$	0.30 to 2.00
	$30^{\circ} < \text{Latitude} < 60^{\circ}$	– 2.00 to 0.50
	Latitude $> 60^{\circ}$	– 1.00 to – 0.20

hydrological processes) and the incorporation of satellite-based observations that provide spatially resolved input to mesoscale models have accelerated research progress in landscape and climate change interactions, compared with twenty years ago (Rau-pach et al. 1999). However, we recognize challenges in this field, and call for improved understanding of the coupled human-climate systems from local to global scales.

#### Research gaps and future research directions

Landscape patterns are shaped by the composition and configuration of land cover. Current studies are mainly focused on the climate response to changes in land-cover composition, while the impact of changes in land-cover configuration on local and regional climate has been less frequently studied and necessitates further investigation. For example, the “fishbone” deforestation pattern has been shown to increase cloud fraction and precipitation under weak synoptic-scale forcing (Roy 2009); landscape heterogeneity due to differential cropland patterns have been shown to enhance mesoscale circulations and precipitation (Weaver and Avissar 2001). From another perspective, which spatial configuration of trees could enhance the recycling of water vapor to the atmosphere and should crops be configured in mosaic or in liner strips to benefit climate and yields are related issues worthy of being studied. In addition to the 2D underlying surfaces, it is essential to understand how the 3D landscape patterns will affect climate on local and regional scales. This is especially important to urban landscapes, because the 3D urban morphology shaped by the composition and configuration of buildings of different heights can vary considerably

in different urban context (Stewart and Oke 2012). Failure to consider the 3D urban morphology will result in large bias in the examination of UHIs (Zhang et al. 2019). Notably, efforts are already being made to improve the representation of urban landscapes in urban climate research by information extraction from high-resolution satellite imagery (Gong et al. 2020).

Different from land cover change, land management change refers to changes in the way in which people treat the vegetation–soil–water system for a particular purpose (Luysaert et al. 2014). Examples of such changes include the employment of fertilizers and pesticides for crop production, the implementation of irrigation and film techniques for mechanized cultivation, the introduction of new grass species for pasture and tree species for forestry, and the adjustment of livestock intensity in a ranching system. Land management changes do not necessarily result in modification of land cover categories (e.g., the conversion of grasslands to croplands), but do result in alterations to land surface biophysical properties (e.g., leaf area index, vegetation fraction, surface albedo, emissivity, roughness length, soil quality, and surface runoff). Currently, except for the irrigation effect, the subgrid-scale landscape heterogeneity arising from land management change has been infrequently explicitly included in mesoscale models, which often assume homogeneous land surface properties for the same kind of land cover category across a grid cell. As a result, such models might fail to characterize key landscape forcing variables at the sub-pixel scale. Fortunately, this situation has been changing in recent years (e.g., the representation of sub-grid landscape heterogeneity is being developed for mesoscale models; Niu et al. 2011).



Prior research has shown that temperature change due to land cover and land management change was of similar magnitude, both on the order of 2 °C (Luysaert et al. 2014). Such work highlights that land management changes have considerable impacts on climate. Indeed, land management practices necessitate consideration for the comprehensive assessment of climate change, especially for regions deriving benefits from the Green Revolution, such as China, India, Europe, and the US (Foley et al. 2005). The representation of land management changes in mesoscale models can be achieved through development of parameterization schemes for a specific region of interest (Zheng et al. 2017). Collaborative, calibrated, integrated, and accessible ground observation networks are essential to achieve this goal. “Superparameterization” that is flexible in terms of scales appears to be a promising approach (Li et al. 2012), which conceptualizes and simulates the land–atmosphere exchange based on the hierarchy theory (Raupach et al. 1999; Wu 1999). Alternatively, advances in satellite techniques make it possible for mesoscale models to represent landscape heterogeneity through incorporation of near real-time and high-resolution satellite-derived land surface products. As an important step forward, Cao et al. (2015, 2018a) examined climate effects of land cover and management changes in the agro-pastoral transitional zone of north China, via incorporation of remotely sensed surface albedo, emissivity, leaf area index, and vegetation fraction into WRF, and found considerable near-surface cooling in summer and warming in winter. However, no signal was detected when merely including changes in land cover types.

Compared with the impact of landscape changes on air temperature, which is well-established, the impact on precipitation is less clear and needs considerable additional research. This is because precipitation is not only affected by regional evapotranspiration but also by large-scale dynamics, although the contribution of landscape-change-induced forcing to total observed precipitation is not trivial (Weaver and Avissar 2001; Gero et al. 2006; Douglas et al. 2009; Nair et al. 2011). For example, our literature review indicates that the increase in precipitation due to agricultural irrigation could range from 25 to 175% across varying geographical regions, through addition of atmospheric moisture and enhancement of the hydrological cycle. In addition to the irrigation amount applied, regional

atmospheric feedback loops and interactions between regional and large-scale circulations also play an important role in determining the magnitude of increase in precipitation, which deserve additional research over the coming years. Likewise, the impact of urbanization on atmospheric circulations (e.g., land-sea breezes) and precipitation (i.e., positive, neutral, and negative) is far from clear. It is also important to know the contribution of the local hydrological cycle as opposed to large-scale dynamics in relation to observed precipitation. For example, Wang et al. (2018) found that about 11% of the urbanization-induced decrease in precipitation over the Beijing metropolitan region was induced by the decrease in local precipitation, while about 89% was due to the decrease in large-scale advected precipitation. A related question is that we currently do not know to what extent landscape alterations will change the precipitation pattern in a region.

#### The role of landscape design in mitigation and adaptation

An important lesson to be drawn from this review is the need to recognize that climate change arises from multiple forcing, and that landscape change must be incorporated in strategies to effectively mitigate and adapt to climate change. Although a majority of studies have been focused on the examination of impacts due to historically observed landscape change on local and regional climate, the emerging interest in climate change mitigation and adaptation through landscape management and planning should also be acknowledged. For example, the deployment of reflective roofs in urban environments has large potential for reducing future urbanization-induced warming under the background of climate change. Findings of this kind, though mainly centered on urban regions, pave the way for the development of a suite of mitigation and adaptation strategies in non-urban environments. However, landscape design is far from mitigation and adaptation, because the socioeconomic dimension is also of vital importance to achieve sustainable development goals (Wu 2013a; Opdam et al. 2018).

Climate regulation is a key ecosystem service, which has become an increasingly important topic in landscape ecology and landscape sustainability (Wu 2013b). However, climate change induced by

landscape changes has historically received little attention from landscape ecologists (Opdam et al. 2009). Landscape sustainability science, with the purpose of designing sustainable landscapes that can maintain or even improve human well-being, provides valuable theories and practical solutions to help land planners and stakeholders deal with the challenge of climate change (Wu 2013a, 2019; Opdam et al. 2018; Frazier et al. 2019). To design sustainable landscapes and achieve landscape sustainability, a theoretical framework should be established first. Such a framework includes: (1) the understanding of linkages between landscape functions and design options; (2) the selection of design approaches based on the relationship between landscape values and functions; and (3) the demand for integrated impact assessments building on the relationship between landscape patterns and ecosystem services (Opdam et al. 2009, 2018; Wu 2013a, b, 2019). With the emerging topic of adapting landscapes to climate change, we believe that landscape ecology and sustainability science will play a pivotal role in the sustainable development of human society.

#### Relationship between climate change and human health

Climate change has a range of consequences for human health, although the need for such work has drawn public attention only in recent decades (Patz et al. 2005; Hondula et al. 2015). The most straightforward relationship between climate change and human health outcomes is the influence of increased extreme heatwaves on heat-related mortality and morbidity in built environments (Wang et al. 2017; Cao et al. 2018b). A recent study has reported a significant increase in mortality risks in China, the most rapidly urbanizing nation in the world (Ma et al. 2015). Indirectly, LUCC-induced climate change can influence the transmission of infectious diseases (e.g., malaria). For example, LUCC may change the behavior of mosquito habitats by modifying local temperature and humidity (Lindblade et al. 2000). In some places, LUCC-induced precipitation change is more important to human health than temperature change, while in other places, the opposite is true (Patz et al. 2005). Moreover, alterations to climate metrics (e.g., planetary boundary layer depth, relative humidity and water vapor, wind speed, and circulation) are

closely related to the horizontal and vertical transport of air pollutants (e.g., particulate matter such as  $PM_{2.5}$ ) and consequently, human health (Georgescu 2015; Li et al. 2015a).

In view of this, it is necessary to extend the scope of LUCC-climate change research to account for human health dimensions. Prior work has calculated the heat stress index (i.e., a combination of temperature, wind, and humidity) to measure human thermal comfort (i.e., the exposure of human bodies to outdoor heat; Willett and Sherwood 2012). It should be acknowledged that the heat stress is far more complex given the ability of humans to adapt to their environments. As a step forward, Kuras et al. (2015) used individually experienced temperatures to account for distinct differences in attributes (e.g., gender, race, and socioeconomic status), behaviors (e.g., schedules, preferences, and lifestyles), and access to resources. In addition, exposure to excessive radiative loading is a critical characteristic that requires incorporation into mesoscale modeling studies focused on heat-health impacts (Hondula et al. 2015). Apart from non-infectious health outcomes such as extreme heat- and cold-related death, climate change and extreme weather events also have profound effects on infectious diseases, as presented earlier. Thus, an in-depth understanding of infectious agents (e.g., protozoa, bacteria, and viruses), their associated vector organisms (e.g., mosquitoes, ticks, and sandflies), and responses of organisms to the changing climate and weather conditions is necessary to reduce the adverse effect of infectious diseases on human health. Importantly, the combined future landscape change and greenhouse-gas-induced climate change may have greater impacts on human health than climate change alone, which requires investigation (Chapman et al. 2017; Krayenhoff et al. 2018).

#### Conclusions

Our review indicates that the literature widely regards landscape forcing as a significant driver of climate change at local and regional scales. The types of landscape changes we examined include urbanization, forest cover change, agricultural development, grassland restoration/degradation, lake desiccation, and dam construction, which have various location-dependent impacts on mesoscale climate. The

development of WRF has facilitated research productivity in this field since 2008, with China and the US being the most widely studied regions. Future research needs to include 2D/3D land cover configuration and land management change in simulating of land–atmosphere interactions. Transdisciplinary approaches that integrate climate science, landscape ecology, and sustainability science are required to achieve sustainable landscapes in the face of climate change. Finally, human health outcomes of climate change and extreme weather events induced by landscape changes (e.g., heat-related mortality, transmission of infectious diseases, and diffusion of air pollutants) should be emphasized.

**Acknowledgements** This study was jointly supported by the Chinese Ministry of Science and Technology through the National Natural Science Foundation of China (41801179 and 41801222) and the National Basic Research Program of China (2014CB954303). MG was supported by NSF Sustainability Research Network Cooperative Agreement 1444758, the Urban Water Innovation Network, and NSF grant SES-1520803. We thank Deyong Yu for his comments on the manuscript.

#### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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