

Review Article

Critical Studies on Integrating Land-Use Induced Effects on Climate Regulation Services into Impact Assessment for Human Well-Being

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It is commonly acknowledged that land use changes (LUC) and climate changes have exerted significant effects on ecosystem services which are essential and vital to human well-being. Among all the services provided by ecosystem, climate regulation services are relatively sensitive to LUC and climate changes. This study aims to comprehensively review studies on the complex effects of LUC and climate changes on climate regulation services and further integrates the effects on climate regulation services into impact assessment for human well-being. In this study, we firstly introduced research efforts in which the drivers of and their corresponding effects on climate regulation services are briefly identified. Then, we explicitly reviewed the researches on the effects of LUC and climate changes on climate regulation services, especially focused on the certain methods and models used to quantify the effects on the major drivers of climate regulation services. After that, the effects of LUC and climate changes on human well-being via climate regulation services were revisited and commented accordingly. Finally, this paper discussed the current research gaps and proposed some research prospects in future studies.

1. Introduction

Land use changes (LUC) and climate changes are two major factors that result in the changes of ecosystem services [1–4]. Along with the socioeconomic development and emerging ecological environmental problems, global changes, and ecosystem services are becoming the research hot topics. The relationships among LUC, climate changes and ecosystem services are interlaced and complex, in which temporal and spatial variations in human-induced LUC and climate variability can result in the difference of ecosystem services [5].

Natural ecosystem delivers a lot of benefits to human beings, and these benefits are known as ecosystem services. According to the Millennium Ecosystem Assessment (2005), these ecosystem services include provisioning services such

as provision of food, water, timber, fiber, and genetic resources; regulating services such as the regulation of climate, floods, disease, and water quality as well as waste treatment; cultural services such as recreation, aesthetic enjoyment, and spiritual fulfillment; and supporting services such as soil formation, pollination, and nutrient cycling [6]. Among all these services, supporting services and regulating services underpin the delivery of other service categories [7]. What is more, there often exist trade-offs between different services when humans make management choices, which can change the type, magnitude, and relative mix of services provided by ecosystems [8]. However, people generally prefer provisioning and cultural services over regulating services [9] thus tend to undervalue regulating services. Consequently, decision-makers often ignore these regulating services in ways that will seriously undermine the long-term existence

TABLE 1: Direct drivers of changes in climate regulation and their corresponding effects, adapted from [18].

Category of drivers	Change of drivers	Effect on climate regulation services
Habitat change: land and sea use	Productive area: expansion, conversion, and abandonment (agriculture, forestry)	Affects carbon sinks and existing stores, greenhouse gas (GHG) emissions, albedo and evapotranspiration, shade, and shelter
	Mineral and aggregate extraction (peat)	Affects soil carbon stores, GHG emissions
	Urbanization and artificial sealed surfaces	Affects soil carbon stores, albedo, shade, shelter, local temperatures, and humidity
Pollution and nutrient enrichment	Pollution emissions and deposition Nutrient and chemical inputs	Affects aerosol sources (soot) Affects GHG emissions
Harvest levels/resource consumption	Livestock stocking rates	Affects GHG emissions
Climate variability and change	Temperature and precipitation	Affects existing carbon stores, evapotranspiration
	CO ₂ and ocean acidification	Affects existing carbon stores, GHG emissions, and aerosol sources
	Sea-level change	Affects existing carbon stores

of provisioning services [7]. The regulating services provided by ecosystems are diverse, among which climate regulation is a final ecosystem service. The ecosystems regulate climate through biogeochemical and biogeophysical processes [6], as sources or sinks of greenhouse gases (GHGs) and as sources of aerosols all of which affect temperature and cloud formation [10–13].

The processes involved in climate regulation include the following: (1) through the CO₂ in the atmosphere was absorbed photosynthesis; (2) evapotranspiration from soils and plants controls the amount of water vapour entering the atmosphere, thus regulating cloud formation and the radiative properties of the atmosphere; (3) the change of the albedo of different land surfaces can affect the climate; for example, the change in vegetation can have a cooling or heating effect on the surface climate and may affect precipitation; (4) the regulation of aerosols comes from soil erosion or vegetation through vegetation scavenging, which affects radiative heating of the atmosphere, surface albedo, and so forth [12].

There are many direct and indirect drivers that can affect the process of climate regulation services. For the systematic understanding of the effect mechanism and quantitative evaluation of the effects on climate regulation, it is important to clarify the major drivers and quantitatively analyze the effects induced by LUC and climate changes on those drivers through both biogeochemical and biophysical process. Comparatively, a direct driver more unequivocally influences ecosystem processes, while an indirect driver operates more diffusely by altering one or more direct drivers; that is, direct drivers have much more explicit effects on ecosystem processes [14] and usually cause physical change that can be identified and monitored [15]. As to climate regulation services, the indirect drivers mainly include demographic drivers (population growth and distribution, migration and ethnicity, etc.), economic drivers (economic growth and consumer choice, market force, industry size and globalization, etc.), and sociopolitical drivers (legislation, regulation, etc.) [16].

The direct drivers are listed in Table 1, among which land use drivers are the most important in the ecosystem context and can be identified as the main drivers of climate regulation [17], while over longer term, climate changes will also have feedback to climate regulation services [18].

In this study, we focus on choosing close researches to explore how LUC and climate changes affect the climate regulation through biogeochemical and biogeophysical processes, respectively. Then incorporating with the effects on climate regulation services and researches on impact assessment for human well-being were further revisited. This study, firstly describes the climate regulation services and the needs and significance to study climate regulation services, then examines how LUC and climate changes affect climate regulation services through review of the researches on major drivers, and after that outlines how changes of the role of ecosystem services in regulating climate affect human well-being through investigation of four major aspects (economic value, extreme weather, food security, and human health) that are closely related with human well-being. This review study intends to provide a reference for the future research on LUC, climate changes, climate regulation services, and human well-being. The framework for the review about the effects induced by LUC and climate changes on climate regulation and further impact assessment for human well-being is shown in Figure 1.

2. Research on LUC Induced Effects on Climate Regulation Services

As mentioned above, LUC plays an important role in climate regulation. Anthropogenic land use has been and will continue to be a major driver of the changes in climate system [17]. And there have been many observations and simulations revealing that LUC exerts effects on climate regulation services through biogeochemical and biogeophysical processes.

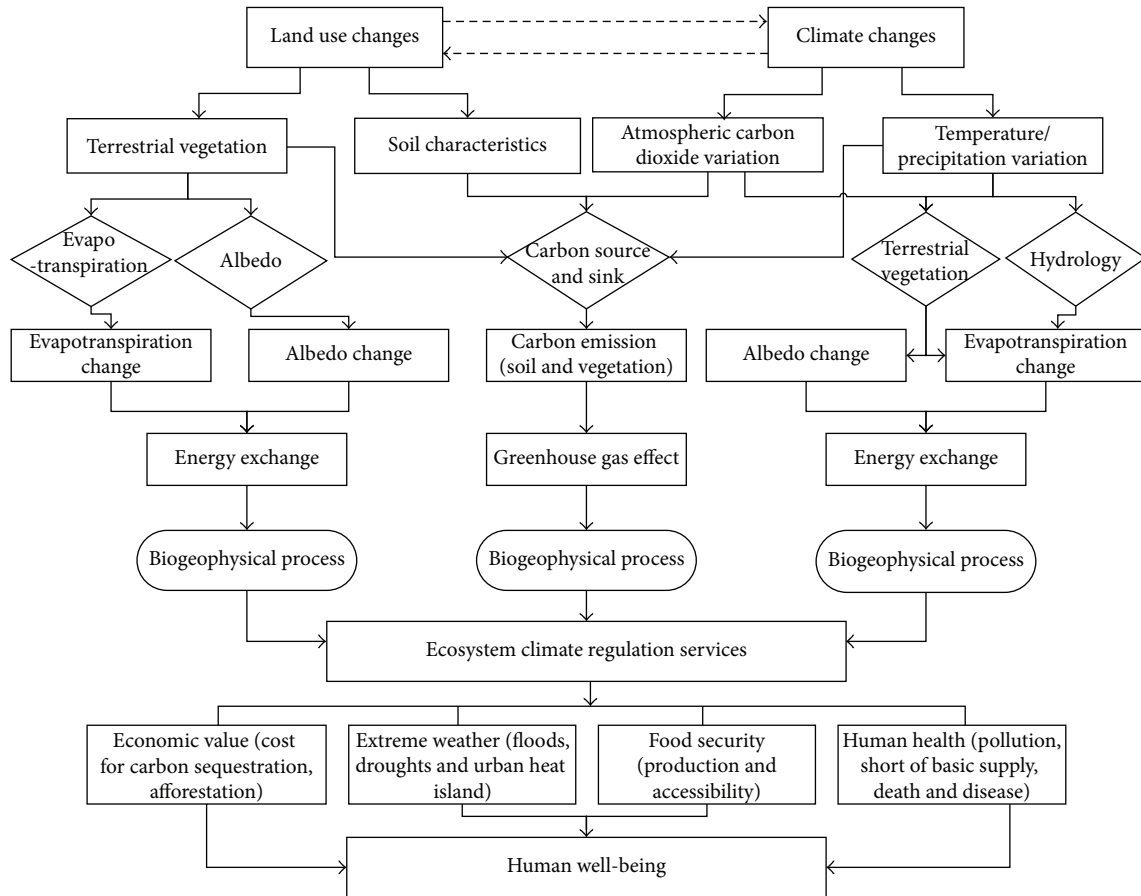


FIGURE 1: Framework for integrating land-use induced effects on climate regulation services into impact assessment for human well-being.

2.1. Consideration of the Cumulative Effects through Biogeochemical Processes. In terms of biogeochemical processes, LUC mainly affects the climate regulation services through the emission and sequestration of GHGs, especially through altering CO₂ flux. The total amount of carbon stored in terrestrial biosphere is an important factor in climate regulation [19]. Terrestrial ecosystems contribute to climate regulation primarily through carbon dynamics. Plants absorb CO₂ through photosynthesis, storing carbon in vegetation and soils, and the carbon accumulated in soil and biomass represents a pool of carbon which is greater than the atmospheric carbon pool [20]. Deforestation, forest degradation, and other land use practices accounted for approximately 20% of global anthropogenic CO₂ emissions during the 1990s [21]. When carbon is released from the earth during cultivation, deforestation, fire, and other land use practices, it binds with other chemicals to form GHGs in the atmosphere and accelerates global climate changes [21, 22]. The conservation of carbon sinks or pools is therefore important to mitigate GHGs levels. Thus it is of great significance to investigate the effect of LUC on climate regulation through its biogeochemical process, that is, through the effects on the cycle of carbon. And LUC can change the release of carbon to the atmosphere mainly through the disturbance on terrestrial vegetation and soils [23].

2.1.1. Biogeochemical Process Related with Terrestrial Vegetation. Terrestrial vegetation is a large carbon sink which plays an important role in the global carbon cycle and is valued globally for the services it provides to society. Vegetation classifications have been related to climate variables and used in assessment of possible global response to climate changes [24–26]. Olson et al. (1983) built up a computerized data base to document the map of vegetation and corresponding carbon density for natural and modified complexes of ecosystems. The map provides a basis for making improved estimates of vegetation areas and carbon quantities [27], illustrating that different types of vegetation have various ability of carbon sequestration. LUC can have great effects on the structure of terrestrial vegetation [28]; for example, once the forest is being converted to cultivated land, the biodiversity will decline. The distribution of sources and sinks of carbon among the world’s terrestrial ecosystem is uncertain, through deforestation, urbanization, expansion of cultivated land, and other land use practices; LUC variously alter the land surface and species compositions and exert various effects on the carbon cycle.

It is relatively difficult to quantify the process that LUC affect the carbon sink or net source of terrestrial vegetation. Most researches developed and applied different models to record the carbon emission or sequestration resulted from

LUC. Firstly, many researchers adopted empirical data to simulate carbon emission and sequestration. Houghton et al. (1983, 1999, 2000, and 2003) calculated the carbon emission resulting from LUC and the potential for sequestering carbon of different land covers mainly based on the parameters set for each vegetation type in each regime [29–36], and the model was called the “bookkeeping” terrestrial carbon model. Further, Houghton et al. (2001) documented a numeric data package that consists of annual estimates of the net flux of carbon between terrestrial ecosystems and the atmosphere resulting from deliberate LUC, especially forest clearing for agriculture and the harvest of wood for wood products or energy from 1850 through 1990 [37]. DeFries et al. (2002) further apply the “bookkeeping” model in conjunction with multiple sources of remote-sensing data to estimate carbon fluxes from tropical LUC [38]. The “bookkeeping” model tracks the amount of carbon released to the atmosphere from clearing and decay of plant material and pluses the amount of carbon accumulated as vegetation grows back. However, the parameters in the “bookkeeping” model are mainly based on empirical data and lack mechanism process. Then some researches started to combine process-based ecosystem models with the “bookkeeping” model, which can associate the land use information with its related process and thus enhanced the accuracy of the estimation. For example, one type of the process-based ecosystem model, the Terrestrial Ecosystem Model (TEM), in which the effect of LUC was characterized by the specific parameters of the function of different vegetation types, can be combined with the “bookkeeping” [19]. And DeFries et al. (1999) predicted the effect of LUC on carbon cycle based on the vegetation distribution information derived from remote sensing data and combined with Carnegie-Ames-Stanford Approach Model (CASA) [39]. What is more, Sitoh et al. (2003) also coupled the “bookkeeping” model with Lund-Potsdam-Jean dynamic global vegetation model (LPJ) [40]. Particularly, McGuire et al. (2001) combined four models, that is, TEM, High Resolution Biosphere Model (HRBM), LPJ, and Integrated Biosphere Simulator (IBIS) model [19]. And Levy et al. (2004) combine the HYBRID vegetation dynamic model with the “bookkeeping” model to estimate the carbon dynamic resulted from LUC [41]. Differently, Schröter et al. (2005) used a range of ecosystem models and scenarios of climate and LUC to assess the vulnerability of ecosystem services, and the simulation results showed that LUC affected terrestrial carbon sink positively through decreases in agricultural land and increased afforestation during the 21th century [1]. Different models have different results about the amount of the carbon emission induced by LUC, but all the results show that global deforestation can lead to large carbon emission.

Among all the vegetation types, forest as one of the productive area is a major part of terrestrial ecosystem. Global deforestation has great effect on the carbon emission [42]. Using forest inventory data and long-term ecosystem carbon studies, Pan et al. (2011) estimated a total forest sink of 2.4 ± 0.4 petagrams of carbon per year (Pg C year^{-1}) globally for 1990–2007, and tropical deforestation around the world contributes to a gross emission of $2.9 \pm 0.5 \text{ Pg C year}^{-1}$, which was equal to 40% of global fossil fuel emissions [43].

Combined with spatial explicit information on changes in forest area which derived from satellite observations and terrestrial carbon models, many researches focused on the tropics to detect whether tropic deforestation act as carbon sink or net source and identified that tropics acted as carbon sink [38, 44]. Explicitly, Arora et al. (2009) assessed the biogeochemical behavior of the CCCma earth system model (CanESM1) against observations for 1850–2000 and then compared simulated atmospheric CO_2 concentration with available observations and observation-based estimates; the simulation results showed that forests’ different photosynthesis ability and CO_2 emissions from LUC resulted in different density of CO_2 in atmosphere, which indicated that the tropics were large carbon sinks [45].

Currently, based on model simulation, it was acknowledged that LUC can affect the carbon sink or source. Firstly, many researches were based on empirical data and statistical models which can use only observation data about the land cover without knowing conversions among different land cover types. While with the application of remote sensing and developed ecosystem models, the carbon emission induced by LUC can be more accurately estimated. However, most models also cannot take some important factors into account, such as the feedback of regional climate change, the water cycle before and after LUC, and the physical structure of soil. More efforts should be devoted to develop models that can comprehensively integrate all the factors to do simulations.

2.1.2. Biogeochemical Process Related with Soil Carbon. The changes of LUC can affect the sink of carbon not only through the sequestration of vegetation covering the land, but also through the changes of soil characteristic of different land cover types. It has been identified that different land cover types’ potentials of soil carbon are various. For example, tropical forests were estimated to store approximately 206 Pg C in the soil globally [4], which was relatively less than half of that of boreal forests’ soil [18, 46]. And explicitly, wet and moist tropical forests tend to have greater soil carbon pools per unit area than tropical dry forests due to higher rates of Net Primary Productivity (NPP) [47]. The potential of cropland soils [48] and grazing land soils [49] to sequester carbon and mitigate the greenhouse effect are different. Dawson and Smith (2009) reviewed effects of LUC and climate changes on soil carbon losses and found that the soil carbon emissions of agriculture land (cropland and grassland), forestry land, and peatlands/wetlands explicitly have different ability of carbon sequestration, and human’s land use management is critical to regulate carbon emission [50].

LUC plays an important role in determining whether soil is a sink or source of atmospheric CO_2 , since it can change the amount of soil carbon sequestration. For example, deforestation can result in an initial loss of carbon from soils due to increased decomposition rates, erosion, and reduced inputs of vegetation residues, namely, soil organic matters (SOM) [51]. Ayanaba et al. (1976) reported that deforestation for cultivated land leads to the reduction of soil total carbon content [52]. As most researches about the effect of deforestation on soil carbon only focused on one kind of land conversion while did not simultaneously take all

the land cover types into consideration, Powers (2004) presented better understanding of the effects of LUC on regional and global ecosystem process by considering all of the land use conversions that occur in the landscape and detect the difference among the effects on soil carbon of each land use conversion based on statistical analyze [53]. Scott et al. (2002) designed a soil carbon monitoring system for New Zealand using country-specific land use and soil carbon information, which can be used to estimate both soil carbon stocks at a single point in time and also future soil carbon stocks in response to LUC [54].

LUC affect the soil carbon content mainly through regulating soil organic carbon (SOC) pools [55]. The dynamic changes of SOC have a strong effect on atmospheric composition and the rate of climate change, thus playing an important role in climate regulation. There have been many studies quantifying the effects of LUC on SOC, and since the carbon dynamics in soil are a long-term process which is relatively difficult for doing field researches and observations, most of the studies were based on model simulations. The major SOM models include SOM model (SOMM), Institute of Terrestrial Ecology-Edinburg (ITE), Verberne, Rothamsted C model (ROTHC), Carbon-Nitrogen-Dynamics (CANDY), DeNitrification and DeComposition (DNDC), CENTURY, DAISY, and NCSOIL, and so forth. Smith et al. (1997) compared these nine models with data from seven long-term experiments representing multiple vegetation and management conditions [56]; the results showed that a comparison of the overall performance of models across all datasets reveals that the model errors of one group of models (ROTHC, CANDY, DNDC, CENTURY, DAISY, and NCSOIL) did not differ significantly from each other. Another group (SOMM, ITE, and Verberne) did not differ significantly from each other but showed significantly larger model errors than did models in the first group. Among all the nine models, ROTHC and CENTURY are two of the most widely used and tested SOM models. Shrestha et al. (2009) used the Century model to simulate changes in SOC pool over 100 years (1950–2050) under managed dense Shorea forest, rainfed upland, and irrigated low land in a midhill watershed of Nepal [57]. And Dieye et al. (2012) analyzed the sensitivity of the GEMS soil organic carbon model in response to LUC [58]; the GEMS model was also developed from the CENTURY model [59]. Barancikova et al. (2010) and Francaviglia et al. (2012) used the ROTHC model to simulate the changes in agricultural land's SOC pools [60, 61]. SOC cannot only be affected by LUC, but also by climate change, which will be revisited in Section 3.1.

2.1.3. Combined Biogeochemical Process of Terrestrial Vegetation and Soil. As mentioned above, most researches focused on the calculation of carbon emission resulted from the terrestrial vegetation changes with different models and methodologies, based on the historical observations or scenarios analysis. And also there are researches trying to figure out the change of carbon emission as the change of soil characteristic of different land cover types resulted from land use management practices. However, it is also important to combine the two biogeochemical processes together to detect

the effect of LUC on carbon cycle and further analyze the effect on climate regulation services.

As to this point of view, Woomer et al. (2004) defined the total carbon in the ecosystem as the sum of the woody biomass, herbaceous biomass, root, litter, and soil carbon pools, and using an inventory procedure involving satellite images which reveal historical LUC and recent field measurements of standing carbon stocks occurring in soil and plant; they estimated Senegal's terrestrial carbon stocks in 1965, 1985, and 2000 [62]. In addition, the changes of carbon emission from vegetation and soil resulted from LUC and climate changes can also counteract with each other. Synthetically considering the carbon emission from vegetation and soil induced by LUC and climate changes, based on a series of ecosystem models and scenarios of LUC and climate changes to evaluate the ecosystem service supply and vulnerability, Schröter et al. (2005) confirmed that Europe's terrestrial biosphere acted as a net carbon sink, with decreased agricultural land and increased afforestation resulting in the increasing sequestered amount of carbon, while soil carbon losses due to warming would balance the carbon sequestered by terrestrial biosphere by 2050 and lead to carbon releases by the end of this century [1]. In the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, a simplified carbon cycle that maps and quantifies the amount of stored and sequestered carbon based on five carbon pools (above ground biomass, below ground biomass, soil, dead organic matter, and harvested wood products) is incorporated [63]. Leh et al. (2013) used average literature values in the InVEST model to calculate the carbon as part of the ecosystem services in major land classes according to the proportion of land use land cover (LULC) area in Ghana and Cote d'Ivoire, West Africa [64]; the model is of great significance to evaluate the ecosystem services.

In summary, effect on climate regulation through biogeochemical process mainly focuses on the carbon emission and sequestration both in terrestrial vegetation and soil; from comprehensive and global perspective, it is important to regulate the carbon cycle to control global warming and there should be more researches to combine the whole biogeochemical processes of LUC's effect on carbon cycle together to provide references for decision-makers to make land use management practices.

2.2. Overall Effects Accounting through Biogeophysical Processes. LUC is a general term for the human modification of Earth's terrestrial surface, and the albedo and evapotranspiration of different surfaces vary with land cover types. The biogeophysical effect mechanisms of LUC on climate regulation are mainly through changing the albedo and evapotranspiration, which are closely related with energy flux between land surface and atmosphere [23, 65–70].

2.2.1. Biogeophysical Process Related with Albedo. Albedo represents the fraction of incoming radiation reflected by the surface. A reduction in albedo means that a larger fraction of the incoming radiative energy is absorbed by the surface, further results in warming [71]. The effect of albedo changes on regional and local climates is a research hotspot,

especially changes in climate in response to changes of vegetated land cover and built-up areas. These changes alter surface heat balance not only by changing surface albedo, but also by altering evaporative heat transfer caused by evapotranspiration from vegetation and by changes in surface roughness [23].

Land surface with different vegetation types possesses different albedos; for example, forests typically have lower albedos than bare ground, grassland, and cropland; therefore, absorb more incoming solar radiation [12, 17], indicating that different vegetation types participated in the land surface play a role in regulating surface energy, thus affecting surface climate. Based on different methodologies and models, there have been many researches focusing on the net radiation associated with the change of albedo resulted from LUC. In the 1970s, Charney (1975) firstly pointed out that albedo changes play an important role in global climate based on Global Climate Model (GCM) and put forward the biogeophysical feedback mechanism [72]. The mechanism explains that vegetation reduction due to drought will lead to increasing the albedo, decreasing the net radiation of the surface and corresponding sensible and latent heat, and further weakening the convergence upward movement, thus resulting in the reduction of cloud and precipitation. It can be seen that albedo plays an important role in surface net radiation and energy exchange. The radiative forcing due to surface albedo change can be simulated with the radiative transfer scheme of the third Hadley Centre Atmosphere Model (HadAM3) [73]. Betts (2000) applied HadAM3 to simulate the radiative forcing associated with changes in surface albedo and revealed that decreasing albedo exerts a positive radiative forcing on climate [65]. Snyder et al. (2004) investigated the participation of different vegetation types within the physical climate system based on CCM3-IBIS (the Community Climate Model coupled to the Integrated Biosphere Simulator), a coupled atmosphere-biosphere model, analyzed the effects of six different vegetation biomes (tropical, boreal, and temperate forests, savanna, grassland and steppe, and shrubland/tundra) on the climate through their role in modulating the biogeophysical exchanges of energy, water, and momentum between the land-surface and the atmosphere, and explained the role of the albedo in modifying the surface radiation budget [70].

2.2.2. Biogeophysical Process Related with Evapotranspiration. Evapotranspiration causes local cooling due to latent heat transfer from the surface to the atmosphere. Evapotranspiration can also influence cloud cover, which, in turn, affects the amount of energy reaching the surface [71]. Clearing vegetation reduces evapotranspiration and associated latent heat flux, as without the vegetation, energy normally used to evaporate water instead of heating the land [17]. Evapotranspiration is an important ecosystem integrity indicator and is strongly related to land cover types. The process of evapotranspiration consumes energy and therefore has a cooling effect and a positive effect on microclimate regulation. To quantify the climate regulation and assess the effect of LUC on climate

regulation, Kroll et al. (2009) used thermal emissions of different land use classes with different land surface emissivity derived from remote sensing data and land cover information of MOLAND classification based on PLUREL scenario [74]. And Twine et al. (2004) analyzed the effects of LUC on the energy and water balance of the Mississippi River basin using the IBIS model, in which the forest cover was assumed to be completely converted to crop cover which resulted in decreasing annual average net radiation and evapotranspiration [75]. In order to assess the effect of LUC on evapotranspiration, Liu et al. (2008) used Dynamic Land Ecosystem Model (DLEM) in conjunction with spatial data of LUC to estimate the LUC's effects on the magnitude, spatial and temporal variations of evapotranspiration in China, and results showed that deforestation averagely increased evapotranspiration by 138 mm/year and urban sprawl generally decreased evapotranspiration 98 mm/year during 1900–2000, and so forth [76]. Yang et al. (2012) first used a knowledge-based decision tree (K-DT) classification technique to detect LUC which was characterized with deforestation and expansion of farmland, barren land and residential land, then a two-source potential evapotranspiration (PET) model was used to estimate the potential evapotranspiration response to LUC, and the result showed a decreasing trend of PET at Shalamulun River watershed in China [77]. And more efforts on quantifying the biogeophysical regulation of climate by ecosystems have largely focused on regional analyses, using GCMs that include land-surface models coupled with atmospheric circulation models, and these regional-scale analyses have focused on areas with strong land-climate feedbacks, including the Amazon [66, 78] and boreal regions [79].

As mentioned above, current approaches for quantifying the biogeophysical regulation of climate by ecosystems (especially through effects on atmospheric heat and moisture) were mainly concentrated on highly complex models, especially atmospheric models, such as HadAM3 and GCMs; thus few nonmeteorologists have access (or the expertise) to run and interpret high complex systems; then West et al. (2010) put forward an alternative approach for quantifying climate regulation by ecosystem; they developed a simple climate regulation index that could quickly produce approximations of biogeophysical regulation of climate by terrestrial ecosystems, in which the potential effects of LUC on biogeophysical climate regulation were estimated based on comparing a natural vegetation scenario to a bare ground scenario [69]. However, conversion of natural land to other land-cover types can have different results; thus the model has potential to be improved.

In some sense, researches of effect on climate regulation of LUC through biogeophysical process are of great significance and mainly focused on the net radiation, energy balance and so forth, which is related with albedo change and evapotranspiration rate. And most researchers simulate the effects with complex atmospheric models, biosphere models, and combined models, and the effect mechanism is relatively similar, while more attention should be paid to how to integrate and simplify the whole process to support most policy-makers, nonmeteorologists, and other related people decision making.

3. Identification on the Effects on Climate Regulation Services due to Climate Changes

According to the forth report of Intergovernmental Panel on Climate change (IPCC AR4, 2007), there is more than 90% probability that human activities have affected the climate [21], mainly through two approaches: fossil fuel burning and land use/cover change. LUC cannot only directly exert effect on the drivers of climate regulation, but also indirectly through its impact on climate changes [80–82]. And climate changes (temperature and precipitation variation and CO₂ variation) are also likely to put many ecosystem services that humans derive from lands, waters, and so forth at risk. Over the long term, climate changes will feed back to climate regulation services [1] also through both biogeochemical and biogeophysical process.

3.1. Biogeochemical Process of the Effect on Climate Regulation Services. The amount of carbon in atmosphere is important to climate regulation services. Climate variations, such as the changes of temperature, precipitation, and atmospheric CO₂ content affect existing carbon stores through biogeochemical process. Friedlingstein et al. (2006) used eleven coupled climate-carbon cycle models with a common protocol to study the coupling between climate changes and the carbon cycle, through the feedback analysis; their results indicated that future climate changes will reduce the efficiency of the earth system to absorb the anthropogenic carbon perturbation [83]. And as to carbon accumulation, soil carbon is a major component of global carbon inventory which interact with atmospheric CO₂. Rising atmospheric CO₂ concentrations will increase radiative forcing and is expected to increase soil temperatures and accelerate decomposition rates of SOC, which, in return, will increase CO₂ accumulation rate in the atmosphere [84–86].

Regarding the temperature changes, which are major elements affecting the photosynthesis [87] and decomposition of SOM [88]. Jenkinson et al. (1991) used the Rothamsted model for the turnover of organic matter in soil to calculate the amount of CO₂ that would be released from the world stock of SOM if temperatures increase as predicted and the annual return of plant debris to the soil being held constant. The results showed that if world temperatures rise by 0.03°C per year, the additional release of CO₂ from SOM over the next 60 years will be 61×10^{15} gC [89]. The temperature's effect on soil carbon losses is also confirmed by recent experimental and modeling studies [90–93] and lots of experimental studies overwhelmingly indicate that increased SOC decomposition resulting from higher temperature led to increased CO₂ emissions from soils [91, 94, 95]. In addition to carbon emission, soil carbon sequestration can be regulated by temperature change [93, 96].

As to moisture or precipitation conditions, in mature tropical forests, soil carbon pools tend to decrease exponentially as the ratio of temperature to precipitation increases, corresponding to a gradient from wet to dry forests [47]. Albani et al. (2006) used ecosystem demography (ED) model, through comparison between the patterns of variability in net ecosystem productivity (NEP) with the patterns of

temperature and precipitation variability from 1948 to 2003 and revealed that the periods of carbon losses during the 1960s were caused by anomalously dry conditions, while the carbon losses that occurred in the late 1990s were due to a combination of reduced precipitation and anomalously warm temperatures in the Eastern US [97]. What is more, to better quantify climate changes' effect on soil carbon, Ise and Moorcroft (2006) used a mechanistic decomposition model in which the effects of temperature and moisture are multiplicative, to estimate the global-scale temperature and moisture dependencies of SOC decomposition, the results indicated that modeling of temperature and moisture dependencies of SOC decomposition in global-scale models should consider effects of scale which were not considered in other models [88]. And as mentioned in Section 2.1.3, SOC can also be affected by climate change. In many SOM models, climate data are important part as the input data into the models, and SOC changes in response to climate changes under different climate scenarios which derived from GCMs and other climate models were usually analyzed [60, 61, 98]. What is more, as the biogeochemical process of carbon sequestration is complex, it is difficult to take into account of all influencing factors; Zhan et al. (2012) used a panel data model and decomposition analyses to figure out the subtle effects of climatic, demographic, geographic, and economic factors, which revealed the importance of climatic factors in carbon sequestration [99].

3.2. Biogeophysical Process of the Effects on Climate Regulation. Human induced climate changes are also important factors affecting the climate regulation services. Along with the industrialization and other human activities, the global climate showed a warming trend, which in the long-term will return feedback to climate regulation services through biogeophysical process.

3.2.1. Effect on Evapotranspiration. Climate changes can exert effects on the hydrological cycle and alter the evapotranspiration that both with implication for ecosystem services and feedback to regional and global climate. Land evapotranspiration is a central process in the climate system and a nexus of the water, energy, and carbon cycles [100]. As evapotranspiration cannot be measured directly at the scale of climate observations and climate predictions, therefore most researches generally applied hydrological models to estimate the effect of climate changes on evapotranspiration [101]; among the models, different PET models are often used. To accurately detect the effect of climate changes on PET, more and more researchers turned over to analyze the sensitivity of these models to climate changes [102–105].

3.2.2. Effect on Albedo due to Changes of Terrestrial Vegetation. Climate changes can also exert effect on climate regulation via the change of vegetation which plays an important role in climate regulation through albedo and evapotranspiration change. The response of terrestrial vegetation to climate changes has long been a research hotspot; there are many studies about understanding and quantifying climate-induced vegetation change [106, 107].

Regarding temperature and precipitation changes, Overpeck et al. (1990) used the FORENA model to simulate the effects of climate changes on four forest types in eastern North America with three types of climate change experiments; the results indicated that climate changes would induce increases in forest and vegetation disturbance, which can significantly alter the total biomass and compositional response of forests to future warming [108]. As anthropogenic increases in the atmospheric concentration of CO₂ and other GHGs are predicted to cause a warming of the global climate by modifying radiative forcing [109], Peters and Darling (1985) had a widespread hypothesis that global warming resulted from greenhouse effect can diminish biological diversity and shift the terrestrial pattern [110]. Moreover, corresponding climate changes with enriched CO₂ may also alter the density of vegetation cover, thus modifying the physical characteristics of the land surface to provide climate feedback. In a vegetation/ecosystem modeling and analysis project (1995), three biogeochemical models (BIOME-BGC (BioGeochemistry Cycles), CENTURY, and TEM) and three biogeophysical models (BIOME2, Dynamic Global Phytogeography Model (DOLY), and Mapped Atmosphere-Plant Soil System (MAPSS)) were applied, respectively, to simulate the geographic distribution of vegetation types under doubled CO₂ and a range of climate scenarios (temperature and precipitation variations), and the results indicated that carbon concentration and temperature and precipitation variations can obviously change the distribution of vegetation types [111]. Betts et al. (1997) used a general circulation model iteratively coupled with an equilibrium vegetation model to quantify the effects of both physiological and structural vegetation feedbacks on a doubled-CO₂ climate, with the output vegetation structure mainly represented by Leaf Area Index (LAI). The results showed that changes in vegetation structure can significantly feed back to regional-scale climate [112]. The vegetation structure feeds back to climate mainly through two opposite effects; increased LAI tended to warm the land surface by lowering its albedo and cool the land surface by enhancing evaporation, while decreased LAI tended to cool the surface via increased albedo and warm the surface via reduced evaporation [79, 113]. To understand how vegetation growth responded to the climatic variations, Piao et al. (2006) took the LAI as an indicator to represent the vegetation activity and based on a mechanism terrestrial carbon model, to detect effect of current climate changes on vegetation growth in the northern hemisphere, and results showed that the vegetation change in different areas can be explained by temperature and precipitation, respectively [114].

Most of the researches focused on terrestrial vegetation ecosystem, while Lovelock and Kump (1994) suggested that if living organism participates in climate regulation in an active and responsive way, they do most probably as part of a tightly coupled system, which includes the biota, the atmosphere, the ocean, and the crustal rock. Within such system, the growth of organisms changes environmental conditions and environmental changes feed back to the growth. Thus they conducted qualitative analysis of the effects of temperature change on the feedbacks induced by changes in surface distribution of both marine algae and land plants, as to detect

how the planetary area occupied by these two ecosystems varies with temperature [115]. There are many kinds of ecosystems on the earth, among which terrestrial ecosystem is much more connected with human beings, while it is also of great significance to do researches that combine other ecosystems with terrestrial ecosystem to comprehensively detect the impact mechanism of LUC and climate changes.

4. Impact Assessment for Human Well-Being due to Land-Use Induced Climate Regulation Services Changes

According to the Millennium Ecosystem Assessment (2005), human well-being is assumed to have multiple constituents, including the basic material for a good life (adequate livelihoods, sufficient nutrient food, shelters, access to goods, etc.); health (feeling well, access to clean air and water, etc.); security (secure resource access, personal safety, and security from disasters, etc.), and freedom of choice and action and so forth [6]. The services provided by ecosystems for all those unalterable needs indicate that ecosystem services are essential to human well-being. Climate regulation relates to the maintenance of a favorable climate, both at local and global scales, which has important implications for health, crop productivity, and other human activities [7]. In this paper, we reviewed how changes in the role of ecosystem services in regulating climate affect human well-being, mainly including economy benefits, food security, human health, and a healthy environment.

4.1. Economic Value Determined by Climate Regulation. Ecosystem services and the natural capital stocks that produce the services are critical to support the earth's life system, contribute to human well-being both directly and indirectly, and therefore represent part of the total economic value of the planet. Costanza et al. (1997) firstly developed the Ecosystem Value System (ESV) calculation system to estimate the economic value of 17 ecosystem services (including climate regulation services) for 16 biomes, in which land use is one of the major factors [116]. Based on the ESV calculation system, some researchers examine the potential effects of the past and future LUC on the ecosystem services [117, 118], and the results showed that the changes of ecosystem services value (among which climate regulation accounted for 10% of the change) in Baguio city about 98% were due to forest cover loss for 1988–2009.

Forest ecosystems play an important role in climate regulation through trapping moisture and cooling the earth's surface, thus regulating precipitation and temperature. Costanza et al. (1997) found that forests yield US\$450 per hectare per year in terms of climate regulation benefits [116]. Explicitly, in the urban context which is directly related with human well-being, urban and community forests can strongly influence the physical/biological environment and mitigate many effects of urban development by moderating climate, conserving energy, CO₂, and water, improving air quality, controlling rainfall runoff, and so forth. As in the case of Tucson, Arizona, each tree would give benefits in the range

of US\$20.75 annually by reducing cooling costs for buildings [119]. Dwyer et al. (1992) calculated that 100 million mature trees in US cities could reduce annual energy costs by US\$2 billion based on computer simulations estimate [120].

LUC and climate changes can exert effect on the capacity of ecosystem to absorb carbon, which will result in the loss of climate regulation services and further loss of socioeconomic benefits. To estimate the value of carbon sequestration in Uganda's protected area, Howard (1995) used two different approaches: first, based on figures of the damage that would occur if the land was converted and carbon released in the atmosphere, the value of Uganda's protected areas as a carbon sink was estimated at US\$245 million, which amounts to a US\$17.4 million annually; second, the replacement cost approach was also used to estimate the cost of replacing this carbon sink functions through an afforestation scheme and was valued at US\$20.3 million annually [121]. The results indicated that along with the degradation or loss of climate regulation services in carbon sequestration, much cost will be input to ecological engineering, such as afforestation and construction of environmental protection area.

4.2. Effects of Extreme Weather Events. In response to ecosystem services changes, extreme weather events directly affect human well-beings, leading to drastic disasters which can influence most aspects of humans, such as living environment, agriculture production, and health. Regional climatic conditions are influenced by changes in ecosystems and landscapes, especially deforestation and desertification. Human-induced alteration of atmospheric composition (the greenhouse effect) also affects climatic conditions. On a large scale, the long-term ongoing GHGs effect will lead to increasing risks of deaths in extreme weather events (heat waves, floods, droughts, etc.) [122]. These events have local and sometimes regional effects, directly through deaths and injuries and indirectly through economic disruption, infrastructure damage, and population displacement. In turn, this may lead to increased incidence of certain communicable diseases as a result of overcrowding, lack of clean water and shelter, poor nutritional status, and adverse effects on mental health.

Climate regulation of hydrology is a research area, in which natural climate system affect hydrology and further exert effect on the runoff, rainfall cyclicality, water quality, soil development, and so forth [123, 124]. As a result, there are marked variations in the likelihood of flooding and droughts, the intensity of erosion and nutrient cycling, and the demand for irrigation water and water supplies, which further will bring substantial loss of human well-being. And as to urban ecosystem, climate changes caused by increased anthropogenic emissions of CO₂ and other GHGs are a long-term climate hazard with the potential to alter the intensity, temporal pattern, and spatial extent of the urban heat island in metropolitan regions [125]. The microclimate regulation of all natural ecosystem in the urban areas contribute to reducing the urban heat island effect, as urban green increases evapotranspiration and therefore has a cooling effect; from the perspective of economics, vegetation can also decrease energy use for heating and air conditioning substantially in

urban areas by shading house in summer and reducing wind speed in winter [126].

4.3. Response of Food Security to Climate Regulation. The accessibility of food is highly dependent on suitable climatic conditions, and the sustainable production of food and raw materials is vulnerable to changes in temperature, precipitation, and concentrations of CO₂. Though the role of climate regulation in food security has not been fully estimated [127], the climate variability which can result from LUC, has been examined as the principal source of fluctuations in global food production in different areas, such as the arid and semiarid tropical countries of the developing world, the northern China, and so forth [128–130]. Specifically speaking, soil carbon sequestration can be regulated by climate changes, especially the changes result from temperature change [93, 96] and LUC. As land is the basic requirement for cultivation of crops, a region's potential for food production in agricultural areas depends directly on the fertility of available arable lands [131], and soil carbon sequestration is a key element for ecosystem biogeochemical carbon cycle and contributes to the formation of fertility in soil, which helps to maintain net productivity, improve water quality, and restore degraded soils and ecosystems [20, 132]. Thus along with the climate regulation services changes, the variability of soil carbon sequestration results in the change of food production and accessibility.

4.4. Consequence on Human Health. In the Millennium Ecosystem Assessment, it was stated that stresses on freshwater sources, food-producing systems, and climate regulation could cause major adverse health effects, and each ecosystem service is sensitive to climate conditions which will be affected by LUC and climate changes. And the change of ecosystem services will affect the human well-being and health of human [122]. Climate regulation is one of the services the ecosystems provide to regulate climate conditions, mainly to ensure that people live an environmentally clean and safe life [133]. The degradation of climate regulation will decrease the ability of ecosystem to avoid the adverse effect of climate changes and can affect human health through both direct effect (such as increasing mortality, diseases from extreme weather) and indirect effects (such as climate-induced changes in the distribution of productive ecosystems and the availability of food, water, and energy supplies). Although climate changes may have some benefits to human health, most are expected to be negative especially in urban areas. As human migrate from rural areas to cities, more than half of the world's population now live in high-density urban areas, many of which are poorly supplied with either ecosystem or human services [122]. And in these urban areas, a reduction in climate regulation services could exacerbate climate stress for large numbers of people, reducing well-being and increasing death rates directly through higher summer temperatures and so forth [16]. Furthermore, climate regulation services of soil carbon sequestration can help mitigate climate changes by offsetting emissions of fossil fuels and reducing GHGs effects, and so forth, which is of great significance to improve environment for healthy lives [132, 134].

5. Concluding Remarks

LUC and climate changes will alter the supply of ecosystem services that are vital for human well-being. The processes through LUC and climate changes influence human well-being via exerting effects on climate regulation services are complex and complicated, involving both biogeochemical and biogeophysical processes. From the perspective of the drivers of and their corresponding effects on climate regulation services, this paper mainly revisited the closely related researches to explore how LUC and climate changes exert effects on the major drivers, such as carbon emission and sequestration, albedo, and evapotranspiration which are key elements to regulate surface energy exchange and further play an important role in climate regulation services. And, along with the changes of climate regulation services resulted from LUC and climate change, different aspects of human well-beings will be impacted which have also been assessed by many researchers. Generally speaking, LUC and climate changes have great effects on climate regulation services. Globally, deforestation, degradation of forest and grassland, land conversion from forest to cultivated land, urban expansion, carbon emission, and so forth all will probably lead to changes in climate regulation services.

So far, lots of researches have been conducted and significant progresses have been made related to each aspect shown in Figure 1. However, there is still room for improvement. First, there have been many methodologies and models developed or enhanced to investigate the effect mechanism of the drivers of climate regulation services via biogeochemical and biogeophysical process, while there are less researches that combine both the processes in the models; thus more research attention should be paid to the effect mechanisms that take both biogeochemical and biogeophysical effects into considerations. Second, in future research, improved models which can combine the effects of LUC and climate changes on the climate regulation as a whole should be developed. In addition, as human well-being changes along with the variation of climate regulation resulted from the effect of LUC and climate changes, further anthropogenic activities and economic development related with human well-being will respond to LUC and climate changes. However, there are relatively less researches that have taken the responses into consideration when assessing the effects, so future research should also focus on these potential societal responses.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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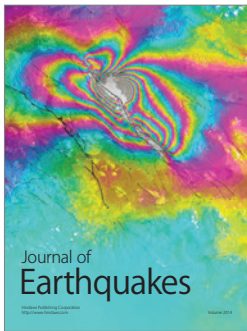
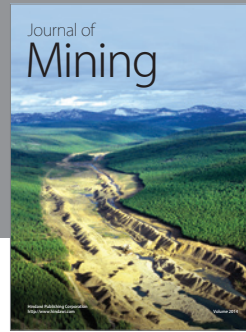
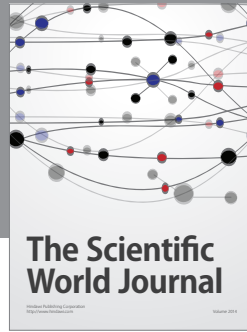
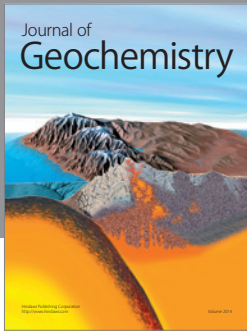
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