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ORIGINAL PAPER

Selecting and applying quantification models for ecosystem services to forest ecosystems in South Korea

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Abstract There is growing interest in using ecosystem services to aid development of management strategies that target sustainability and enhance ecosystem support to humans. Challenges remain in the search for methods and indicators that can quantify ecosystem services using metrics that are meaningful in light of their high priorities. We developed a framework to link ecosystems to human wellbeing based on a stepwise approach. We evaluated prospective models in terms of their capacity to quantify national ecosystem services of forests. The most applicable models were subsequently used to quantify ecosystem services. The Korea Forest Research Institute model satisfied all criteria in its first practical use. A total of 12 key ecosystem services were identified. For our case study, we quantified four ecosystem functions, viz. water storage capacity in forest soil for water storage service, reduced suspended sediment for water purification service, reduced soil erosion for landslide prevention service, and reduced sediment yield for sediment regulation service. Water storage capacity in forest soil was estimated at 2142 t/ha, and reduced suspended sediment was estimated at 608 kg/ha. Reduced soil erosion was estimated at 77 m^3/ha, and reduced sediment yield was estimated at 285 m^3/ha. These results were similar to those reported by previous studies. Mapped results revealed hotspots of ecosystem services around protected areas that were particularly rich in biodiversity. In addition, the proposed framework illustrated that quantification of ecosystem services could be supported by the spatial flow of ecosystem services. However, our approach did not address challenges faced when quantifying connections between ecosystem indicators and actual benefits of services described.

Keywords Classification · Ecosystem services · Quantification · Stepwise approach

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Introduction

Ecosystem services support human well-being in many ways. They provide us with food, feed, fiber, and ecological resilience to climate change. Evaluation and estimation of ecosystem services have been recognized as important parts of science. They provide crucial information for management and policy governance (MA 2005).

Various approaches have been used to assess ecosystem services to facilitate decision-making and improve management. Demand for reliable information to be used in policy-making has been highlighted as an important aspect

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of ecosystem evaluation (Frélichová et al. 2014; Maes et al. 2012; Perrings et al. 2011). Assessment of ecosystem services is needed at the national level to support policy makers when applying these concepts and their values.

Following study of Costanza et al. (1997), scientific ecosystem approach can estimate and map the global value of ecosystem services in monetary terms. The most common scientific approach applied is quantifying and mapping-based assessment procedure (Cowling et al. 2008; Haines-Young and Potschin 2010). Quantification and mapping of ecosystem services, in both biophysical and economic terms, are important to enact effective decision-making and to enhance policy implementation (Burkhard et al. 2009, 2012; Daily and Matson 2008). Quantitative spatial information on the delivery of ecosystem services provides baseline data so that future net gains or losses can be measured (Maes et al. 2012).

Numerous approaches and methodologies have been proposed to quantify and map ecosystem services (Burkhard et al. 2009; Costanza et al., 1997; Egoh et al. 2008; Naidoo et al. 2008; Nelson et al. 2009; Willemen et al. 2008). These approaches vary in scale, scope, and method. For example, Egoh et al. (2008) mapped ecosystem services and assessed spatial congruence and relationships between five soil and water related ecosystem services (surface water supply, water flow regulation, soil accumulation, soil retention, and carbon storage) in South Africa. Willemen et al. (2008) quantified and mapped relationships between landscape functions and landscape properties in order to describe ecosystem services. Naidoo et al. (2008) quantified four ecosystem services at global level. Burkhard et al. (2009) presented a method of mapping ecosystem service supply. Nelson et al. (2009) compared biodiversity conservation and ecosystem service outcomes by using a spatially explicit model called Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST). Despite the large number of studies, the proposed methods are not directly applicable to biodiversity-related policy-making at national or regional levels due to the lack of applicable data. Literature or expert based approaches can provide reasonable solutions where appropriate data are lacking (Burkhard et al. 2012; Haines-Young et al. 2012; Koschke et al. 2012). Monitoring schemes dedicated to ecosystem services have been suggested as a solution for the lack of data (Burkhard et al. 2012).

From the perspective of sustainable management in South Korea, forest ecosystems are key providers of ecosystem services (Kim et al. 2010). The consequences of increased interaction between people and forest ecosystems have received considerable attention in recent years through a green infrastructure approach (MOE 2014). While the importance of spatial analysis and quantification of ecosystem services has been increasingly recognized in the context of forest ecosystem conservation, ecosystem service quantification has rarely been considered in South Korea due to methodological challenges. In this study, we proposed a methodology for quantifying ecosystem services provided by forest ecosystems at national level. Our quantification was based on existing methods for mapping and quantification of forest ecosystem services. We tested our proposed methodology in South Korea and analyzed available ecosystem services to help support management decisions and policy making.

Methods and materials

Methods

We classified ecosystem services based on modifications of an existing framework used to classify ecosystem services along functional lines (MA 2005). We categorized ecosystem services into provisioning, regulating, cultural, and supporting services based on their relevance, present conditions, and significance in quantifying ecosystem services in South Korea. The definition of each category of ecosystem service was scrutinized for relevance at forest environment level. The classification was reviewed to quantify forest ecosystem for spatial analysis.

This approach was taken to enable the use of national databases to analyze the effectiveness of previously proposed methods for quantification of ecosystem services. Based on consensus of national experts, three steps were taken to select methodologies to quantify ecosystem services in this study. First, we reviewed methodologies of previous studies, their underlying assumptions, and limitations. The relevance of various ecosystem services in previous studies (Boyd and Banzhaf 2007; Dominati et al. 2010) was also checked. We examined research approaches that actively used ecosystem services concepts in all parts of South Korea. We also examined research approaches that covered most important aspects of ecosystems and their services including ecosystem properties and geo-biophysical features such as land cover, primary production, and topography. Second, we considered the suitability of the different evaluation methods. The selection of suitable method is important for ensuring the quantification of ecosystem services. We reviewed the most appropriate methods, and selected some methods that could be applied to Korean data, otherwise we checked if methods could be improved. Improvable methods were then selected for our analyses. Third, we considered whether data or acceptable proxies were available for ecosystem services quantification. Expert evaluation was used to determine whether quantitative ecological data used in previous studies or national statistical data could be used in this study. We constructed alternative datasets when the required input data were not available (Fig. 1). Forty experts, including academic and agency scientists, met and assessed this methodological approach to ensure its validity.

Study area and materials

Study area

Our study area covered the entirety of South Korea, 124°54′–131°06′E and 33°09′–38°45′N. The terrain of South Korea is mostly mountainous, with high elevations in the east and low elevations in the west and south (Fig. 2). The total forested area of the country is 6,369,999 ha, accounting for 64 % of the total territory. The distribution of forest area by age-class is: 2,023,000 ha, or 32 % of the total forest area, comprised of trees under 30 years old and 4,142,000 ha, 65 %, of trees over 31 years old. The dominant vegetation type is needle-leaved forest that covers 42 % of the area, while broad-leaved forest covers 26 % and mixed forest covers 30 %, all providing rich habitat for wild animals (KFRI 2011).

Forest ecosystem services

Our classification was based on the quantification and spatial characteristics of ecosystem services. An indicator should yield information that can be quantified as a variable. Indicators were divided into four categories in line with the ecosystem functions typology proposed by MA (2005). Selected ecosystem functions for the services can be assessed on a unit area basis (grid cell) and referred to the ecosystem's capacity to provide a service. We classified forest functions into 4 ecosystem services as follows; provisioning services such as water storage, genetic resources, forest products; regulating services such as air quality, climate regulation, water purification, landslide hazard regulation, and sediment regulation; cultural services including recreation, and cultural heritage; and supporting services such as habitat suitability and nutrient cycling (Table 1).

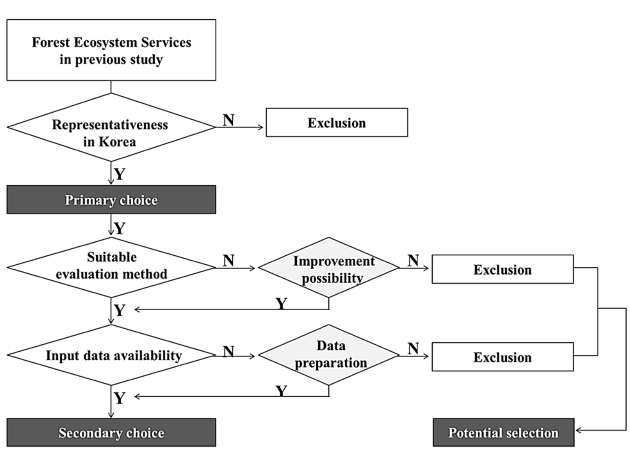

Fig. 1 Application of the ecosystem services quantification framework in South Korea

Model selection and application for forest resources

We analyzed 14 models based on their quantification frameworks for ecosystem services (Fig. 1) to identify models suitable for South Korea after considering indicators listed in Table 1. We compared models to quantify ecosystem services and checked availability of input data for applying models to forest ecosystem of South Korea.

Results

Ecosystem services quantification models

Selection of models

Through literature reviews and discussions with forty experts, we assessed 14 models based on their evaluation criteria, analytical and modeling approaches, potential for quantifying and evaluating ecosystem services, data requirements and outputs (Table 2). We used these models to assess and classify ecosystem services. Most ecosystem service models tend to focus on provisioning and regulating services. Such models can provide spatially explicit evaluation on a global scale. However, they cannot be practically applied for regional studies. In addition, large scale models such as the Asian Pacific Integrated Model (Matsuoka et al. 1995), Co$ting Nature (Mulligan et al. 2010), Global Unified Metamodel of the BiOsphere (Boumans et al. 2002), Integrated Global System Model (Paltsev et al. 2005), Integrated Assessment Modeling Framework Including IIASA-ECS modeling (Keppo et al. 2007; Riahi and Roehrl 2000), Integrated Model to Assess the Global Environment (Bouwman et al. 2006), and Multiscale Integrated Models of Ecosystem Services (Boumans and Costanza 2007) were developed to promote integrated assessment. These spatially explicit and integrated models are associated with biosphere and atmosphere. CENTURY (Parton et al. 1988) and Integrated Biosphere Simulator (Kucharik et al. 2000) are two models that simulate biogeochemical processes of terrestrial ecosystem exchanges. These models can explain vegetation processes and simulate external effects. The following five models are for regional land use; Artificial Intelligence for Ecosystem Services (Bagstad et al. 2011), Advanced

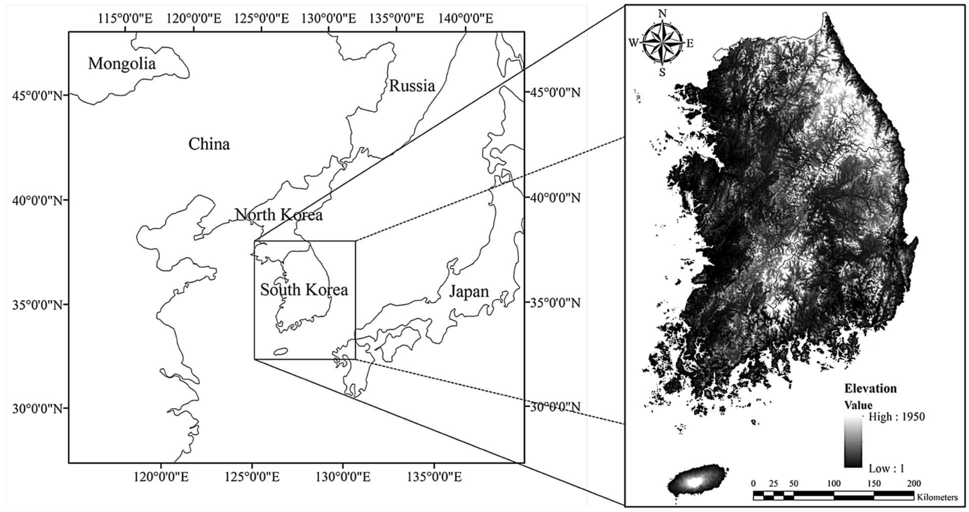

Fig. 2 Study area with Digital Elevation Map (DEM)

Terrestrial Ecosystem Analysis and Modeling (Schröter et al. 2004), Integrated Valuation of Ecosystem Services and Tradeoffs (Sharp et al. 2014), Patuxent Landscape Model (Villa et al. 2004), and Korea Forest Research Institute (Kim et al. 2010). These models are suitable for assessing processes and ecosystem services at regional level. They are characterized by thematic coverage and input variables. Although these models can be adapted to quantify ecosystem services, they are constrained by data availability. Hence, building input data is a necessity.

We followed evaluation criteria (Fig. 1) and assessed all four categories of ecosystem services proposed by Bagstad et al. (2013). Criteria for each model are summarized in Table 3. Application of these criteria revealed that the KFRI model could satisfy all criteria for its first practical use. The KFRI model used statistical and Geographic Information System (GIS)-based techniques. It can be used to estimate spatial unit value. It is a simplified method for forest ecosystem estimation in South Korea.

Input data availability

The availability of input data for modeling is summarized in Table 4. We searched for input data covering soil and vegetation classification, topographic information and climatic data at varying temporal and spatial resolutions. These data sources were not directly applicable to quantify ecosystem services at the national level. Thus we produced additional datasets in cooperation with the Korean Forest Service (KFS). We used 1:50,000 scale land cover maps developed by MOE (http://egis.me.go.kr) of South Korea as reference maps. Topography, forest, and geology databases were constructed. A current forest map using 1:25,000 scale and 1:50,000 scale geological maps was constructed using GIS. Forest type, height, age, and density were extracted from the forest map. Forests were assumed to be 5, 15, 25, 35, 45, and 55 years old for age classes I, II, III, IV, V, and VI, respectively, as reported in KFS data. Parent rocks and lithologies were extracted from the geological map. Precipitation data were obtained from seventy-five weather stations of Meteorological Agency in South Korea (Korean Meteorological Administration, KMA). Data for unmonitored points were obtained by inverse distance weighted (IDW) interpolation methods using GIS software ARC/INFO. All spatial data sources were converted to raster format with a spatial resolution of 10 m × 10 m.

Application of selected models

Selection of ecosystem functions for the services and method to apply models in Korea

Criteria used to select indicators and quantification methods were based on suitable evaluation methods and on data availability. Each indicator had to be spatially explicit and credible (de Groot et al. 2010). Four ecosystem functions for the services were selected based on the characteristics of the study area: (1) water storage capacity in forest soil for water storage service, (2) reduced suspended sediment for water purification service, (3) reduced soil erosion for landslide prevention service, (4) reduced sediment yield for sediment regulation service (Table 5). Water storage capacity was defined as the amount of water stored in the forest soil in this study. The water storage capacity model was developed using soil depth and porosity recorded on the geological map. We assumed that water purification is to reduce suspended sediment. The suspended sediment model can estimate the quantities of suspended solids based on annual precipitation and run off in clear cutting

Table 1 Selected ecosystem services and indicators used to quantify forest ecosystem services in South Korea

Ecosystem services	Selected ecosystem functions for the services	Indicators of selected functions and measurement units	Issues related to assessment
Provisioning			
Water storage	Water storage capacity in forest soil	Soil depth (cm), porosity (%)	
Genetic resources	Maintaining the diversity of genetic resources	No indicators complied	Complex to quantify genetic diversity and variation
Forest products	(Non-timber) Forest products	(Non-timber) Quantity of forestry production	
	(Timber) Net forest growth	(Timber) Net annual growth, net annual growing stock	
Regulating			
Air quality	Absorption of atmospheric pollutants (SO_2, NO_2, and PM10) in forest	Air pollutant concentration of SO_2 (ppm), NO_2 (ppm), PM10 ($\mu g/m^3$), wind speed (m/s), dry weight growth by tree type (t/ha)	
Climate regulation	Carbon storage and sequestration	Height (m), DBH (cm), stem volume (m^3), stem biomass (kg), above ground biomass (kg), whole tree biomass (kg), basic wood density, biomass expansion factor, root shoot ratio, carbon fraction	
Water purification	Reduced suspended sediment	Precipitation (mm), suspended sediment concentration (ppm), runoff discharge (1/s)	
Landslide prevention	Reduced soil erosion	Slope failure volume (m^3), sediment yield (m^3)	
Sediment regulation	Reduced sediment yield	Ratio of the parent material (%), sediment yield in non-stocked land (m^3), sediment yield of the parent material by stand age class (m^3/ha)	
Supporting			
Habitat suitability	Providing suitable habitat	Distribution of species	
Nutrient Cycling	Nitrogen (N) cycling	Fluxes of NO, N_2O, and CH_4, soil bulk density, particle size, soil pH, net nitrification, gravimetric water content	Difficult to quantify natural N flows and insufficient information
Cultural			
Recreation	Recreational function of the forest	Space available for recreation and km^2 for recreation use	May not necessarily reflect change in ecosystem and difficult to distinguish the specific contributory role
Cultural heritage	Heritage in forest	Species, cultural custom, habitat	Difficult to quantify cultural custom and Insufficient information

area. The reduced soil erosion is considered in terms of landslide hazard. The reduced soil erosion in forests is related to annual landslide rate and the percentage of ground cover. We defined the reduced soil erosion as the prevention of landslides with failure volume. Slope failure volume was compared the amount of slope failure from stocked land area compared to the amount of slope failure from non-stocked area. The reduced sediment yield was calculated as the difference of sediment yield by parent materials between stocked and non-stocked area. The reduced sediment yield model would link average stand age to sediment yield. The sediment yield differed depending on the type of parent rock. It was calculated by comparing the sediment delivery ratio and potential soil loss, using a forest type map.

Application of selected model to forest ecosystem in South Korea

The KFRI model for the assessment of non-market benefits of forest (Kim et al. 2010), was used based on stepwise quantification application-based framework. The four forest ecosystem services indicators used for quantification are shown in Fig. 3. Some locations were estimated to

Table 2 Input and output factors of models

Models	Input factors	Output factors	Quantifiable approach
AIM	Temperature, wind speed rainfall, cloudiness, soil texture, soil unit, soil phase, field capacity	Energy consumption, land use change affecting water supply, vegetation changes, human health	✔
ARIES	Stored c release (fire, land use change, other disturbance), property/housing value, rainfall, snowmelt, climate, fishing grounds, vegetation, coral reefs, and topographic features, areas where sedimentation is desirable, areas where sedimentation is undesirable, areas where excessively turbid water is undesirable, surface water withdrawals or wells, recreationists interested in a given activity	Carbon sequestration and storage, aesthetic viewsheds and proximity, flood regulation, subsistence fisheries, coastal flood regulation, sediment regulation, water supply, recreation	✔
ATEAM	Socioeconomic factors, atmospheric greenhouse gas concentrations, climate factors, and land use	Vulnerability map for agriculture, wood production, carbon storage, soil fertility, biodiversity, natural beauty	✔
CENTURY	Temperature, precipitation, soil texture, soil C, N, P and S amounts	Evapotranspiration, soil water content, soil organic matter (C, N)	✔
Co$ting Nature	Global simTerra database (400+ grids), cropland cover area, Sustainable and the Global Environment (SAGE)	Pressures, threats, overall relative conservation priority to water, carbon, tourism, hazard mitigation, biodiversity, protected area	✔
GUMBO	Population growth, Gross World Product changes, changes in global temperature	Human capital, social capital to produce economic goods and services, social welfare, monetary values for 11 ecosystem services, per capita food and welfare	✔
IBIS	Temperature, precipitation, wind speed, radiation, atmospheric pressure	Evaporation, transpiration, soil organic matter (C, N), GPP, NPP, NEP	✔
IGSM	Capital, labor, land, fossil energy reserves	Emission greenhouse gases, temperature, precipitation, sea level rise	✔
IIASA	Population development, economic development, technological change, environmental policies, energy intensity	Greenhouse gas emission, temperature change, development of least-cost mitigation scenarios, water supply and demand (water scarcity index), crop production	✔
IMAGE	Population projections, economic drivers, technological development, policy options	Concentrations, emissions, energy, climate, effects of climate, land use, food production and demand	✔
InVEST	Land use maps, basic information about the landscape, land quality, management practices, infrastructure and governance	Future land use, potential water yield, carbon sequestration, agricultural production, biodiversity, balance sheets for trade-offs between ecosystem services, optimal land allocation for different services	✔
MIMES	Climate, land use, socio-economic drivers	Global temperature, atmospheric carbon, sea level, water, fossil and alternative energy, consumption, area of different land covers, knowledge, human, built and social capital, physical and monetary values for 11 ecosystem services, per capita food and welfare	✔
PLM	Human land use policies, land management (N), climate	Land use pattern, water quality, NPP, water cycle, soil nutrients	✔
KFRI	Soil depth, porosity, forest type, parent rocks type, biomass	Water storage, landslide prevention, CO_2 storage, O_2 production, water purification, sediment regulation	✔

provide high values of ecosystem services. For reduced soil erosion and water storage capacity in forest soil, hotspots with high levels of ecosystem services were distributed around Baekdudaegan Mountains, a protected area with rich biodiversity (Heo et al. 2010) (Fig. 3a, c). In this area, ecological corridors are used to maintain linkages, conserve biodiversity, sustain ecosystem services, and restore cultural values. These corridors also provide water resources, climate regulation, timber, and forest products (Heo et al. 2010). The reduced suspended sediment is generally uniformly distributed at national level with higher values concentrated around the capital region (Seoul, Incheon, and Gyeonggi-do) (Fig. 3b, d). This result is expected because Seoul and Gyeonggi-do began to develop green infrastructure and plant water-purifying vegetation with the aid of the Green Fund Management Foundation (KFS, http://forest.go.kr) in 2006.

Table 3 Criteria used for model selection

Models	Applicable to forest ecosystem	Need improvement to apply model	Mainly use public data	Ecosystem services
AIM	Yes	Yes	Yes	No
ARIES	Yes	No	Yes	No
ATEAM	Yes	Yes	Yes	Yes
CENTURY	Yes	Yes	Yes	No
Co$ting Nature	Yes	No	Yes	No
GUMBO	No	Yes	Yes	Yes
IBIS	Yes	Yes	Yes	No
IGSM	No	Yes	Yes	No
IIASA	No	Yes	Yes	No
IMAGE	Yes	Yes	Yes	No
InVEST	Yes	Yes	Yes	Yes
MIMES	Yes	Yes	Yes	No
PLM	Yes	Yes	No	No
KFRI	Yes	No	Yes	Yes

AIM Asian Pacific Integrated Model, *ARIES* Artificial Intelligence for Ecosystem Services, *ATEAM* Advanced Terrestrial Ecosystem Analysis and Modeling, *GUMBO* Global Unified Metamodel of the BiOsphere, *IBIS* Integrated Biosphere Simulator, *IGSM* Integrated Global System Model, *IIASA* IIASA Integrated Assessment Modeling Framework, *IMAGE* Integrated Model to Assess the Global Environment, *InVEST* Integrated Valuation of Ecosystem Services and Trade-offs, *MIMES* Multiscale Integrated Models of Ecosystem Services, *PLM* Patuxent Landscape Model, *KFRI* Korea Forest Research Institute Model

To evaluate the accuracy of quantification for the four forest ecosystem services, our results were compared to those of previous studies in South Korea. To our knowledge, no other spatially explicit information was available. A total of four estimates (Kim et al. 2010, 2012; Lee et al. 1989; Lee 1995) were available for comparison at national level. An overview of various estimates based on unit area is shown in Table 6. In term of reduced soil erosion and reduced sediment yield, the estimates made by previous studies were similar to ours. Our reduced suspended sediment (608 kg/ha) was similar to the 600 kg/ha estimated by KFS. Kim et al. (2012) reported a much lower estimated value at 151 kg/ha due to different unit value. In terms of water storage capacity in forest soil, wide ranging estimates were obtained. This might be due to stand age, soil conditions and forest evapotranspiration. The water consumed by a forest accounts for approximately 14 % of rainfall in South Korea (Chung 1998) excluding evapotranspiration and discharge. Annual precipitation is 1200 mm. Sediment transport from forests is approximately 0.6 t/ha/year (KFS 2010). According to KFS (2007), water storage capacity in forest soil is approximately 18.6 % from managed forests and 15.5 % from unmanaged forests. Water storage capacity in forest soil was approximately 10 % of rainfall in the forest examined. It is related to forest characteristics. For more accurate quantification, it is necessary to monitor changes in water storage and discharge with flow. It is also important to compare hydrological parameters in managed and unmanaged forests. The sediment regulation in forest has been estimated at 500 million m^3/yr, 0.9 t/ha of stocked forest area, and 118 t/ha of non-stocked forest area (Forest Products Distribution Information System website, cited 13 May 2014). However, we did not consider forest characteristics, nitrogen, phosphorus loads, or chemical oxygen demand in this study. Future research is needed to address the removal of pollutants based on unit area.

Discussion

Quantification framework

This study described a framework for quantifying ecosystem services. It provided detailed spatial assessments at national level. Our approach followed the stepwise framework used by the European Union (2014). This study tested a framework that could be used to distinguish quantification and spatial distribution derived from biophysical data. This is the first application of this framework by focusing on biophysical aspects and underlying provisions of ecosystem services. A framework to quantify ecosystem services can provide information needed to identify spatial dependence at national level. Our framework enables such analysis in a structured and stepwise

Table 4 Availability of input data for modeling

Class	Applicable input factors	Map scale in South Korea	Source
Climate	Humidity		Korea Meteorological Administration
	Precipitation		Korea Meteorological Administration
	Temperature		Korea Meteorological Administration
Topography	Slope	Topographic map 1:5000	National Geographic Information Institution, Ministry of Environment
	Land cover	Topographic map 1:5000	National Geographic Information Institution, Ministry of Environment
	Aspect	Topographic map 1:5000	National Geographic Information Institution, Ministry of Environment
Soil	Soil erosion	Soil map 1:25,000	Korea Forest Service, Water management Information Networking System
	Soil evaporation	Soil map 1:25,000	Aerial photography, Korea Meteorological Administration
	Soil texture	Soil map 1:25,000	Korea Forest Service, Soil Groundwater Information System under Ministry of Environment
	Soil depth	Soil map 1:25,000	Korea Forest Service, Water management Information Networking System
Forest	Biomass		Korea Forest Service
Vegetation	Vegetation Type	Land cover map 1:50,000 Forest type map 1:25,000	Ministry of Environment
	Density	Land cover map 1:50,000 Forest type map 1:25,000	Korea Forest Service
Water	Groundwater well		Korea Rural Community Corporation
	Water table depth		Korea Rural Community Corporation

manner, thereby avoiding confusion between ecosystem properties and services (Bateman et al. 2011). This framework was applied to South Korea to quantify ecosystem services by combining various sources of information. This framework provides a flexible classification and quantification system by focusing on provisioning and regulating ecosystem services, both of which are important for green infrastructure. In addition, the approach can be linked to the value of ecosystem services per unit area. This framework can help us determine quantitative assessment steps to evaluate ecosystem services. The methodological framework introduced in this study may help other countries quantify natural resources and develop maps or other indicators at national level. In this analysis, we found that there was a gap between process and application in the quantification of ecosystem services. Such gap should be considered for quantifying the ecosystem services. For example, some indicators could be added for ecosystem quantification. Therefore, it is necessary to develop indicators based on quantitative information.

Quantification and indicator selection

Although some ecosystem services can be quantified using existing methods and data (i.e., water storage of provisioning service), others require different kinds of data and methods (i.e., cultural heritage of cultural service). Depending on the scale, different quantification and mapping methods might be needed (Müller et al. 2010). Data limitation is a common and major challenge during the construction of framework and methodology for ecosystem services quantification. Selecting the best available model based on data availability is fundamental for ecosystem quantification (Bagstad et al. 2014). In this study, the KFRI model was chosen to assess ecosystem services based on its methodological approach and data availability. Compared to other quantification models, the KFRI model can provide estimates at national and regional scales. In addition, it can utilize publicly accessible environmental data. Furthermore, it can be applied to estimate the economic value of services by using quantification per unit area based on category. For example, the quantification by forest type in South Korea (Table 7) can be performed. To avoid over-estimation and under-estimation, unit based economic valuation is possible using the KFRI model. However, further data from field surveys (e.g., biophysical data, hydrologic conditions of soil) will be needed to reduce uncertainty and provide ecosystem services flow mapping.

It is expected that ecosystem service indicators will not be adequate to provide a full understanding of the quantity of services that ecosystems can provide (Layke 2009). It is challenging to assess the indicators that reflect the ecosystem services concept at national level. Although we applied existing ecosystem service methods and indicators, we did not take into account multiple scales or ecological boundaries. In addition, the definition of ecosystem service

Table 5 Indicators of selected functions for the services and method selected for this study. *Source*: Kim et al. (2010)

Ecosystem services	Selected ecosystem functions for the services	Indicators of selected functions and measurement units	Method
Provisioning			
Water storage	Water storage capacity in forest soil	Soil depth (cm), porosity (%)	Soil depth by parent rock type × Porosity by forest type
Regulating			
Water purification	Reduced suspended sediment	Precipitation (mm), suspended sediment concentration (ppm), runoff discharge (1/s)	Suspended sediment concentration × Runoff discharge Suspended sediment concentration = Precipitation × 0.18 + 8.09 Runoff discharge = Precipitation × 9.2
Landslide prevention	Reduced soil erosion	Slope failure volume (m^3), sediment yield (m^3)	Slope failure volume + Sediment yield Slope failure volume = (Slope failure volume in non-stocked land − Slope failure volume in stocked land) × Forest area Slope failure volume = 114.14 × ln(Stand age) + 133.19 Sediment yield = (Average sediment yield differences between non-stocked land and stocked land × Landslide area in stocked area) × Forest area Slope failure area = 0.0114 × ln(Stand age) + 0.0147
Sediment regulation	Reduced sediment yield	Ratio of the parent material (%), sediment yield in non-stocked land (m^3), sediment yield by the parent material and stand age (m^3/ha)	$\sum$(Area ratio by parent material × Sediment yield by parent material in non-stocked area) − $\sum$(Area ratio by parent material × Sediment yield by parent material and stand age in stocked area) × Stocked area Sediment yield from igneous rock = 1.4431 × exp(−0.0233 × Stand age) Sediment yield from metamorphic rock = 4.7115 × exp(−0.0694 × Stand age) Sediment yield from sedimentary rock = 1.2808 × exp(−0.028 × Stand age)

indicators is not consistent. Ecosystem services are commonly divided into four categories following CICES (2013), MA (2005), and TEEB (2010). Indicators used are different. From multiple appropriate indicators, we should select the one that can be used to quantify ecosystem services. In this study, we recognize that ecosystem service classification is a useful concept to frame spatially explicit quantitative assessments of ecosystems and their benefits. However, several challenges remain when evaluating ecosystem services at the national level. In this study, we focused on the provisioning and regulating services of ecosystem without including human activities such as water provision and consumption. Relationships between studied indicators and their actual benefit to humans at national level should be considered.

Conclusions

This study describes a framework to quantify ecosystem services using spatially explicit data available for South Korea. We provide a conceptual approach for quantifying forest ecosystem services. The framework enables the selection of suitable model to quantify ecosystem services at national level. The appropriate selection of model can be used to provide spatial quantification of ecosystem services for supporting management decision and policy making. We suggest that ecosystem service quantification follow this structured framework, select the most appropriate model, and indicator per ecosystem service. The framework is useful to better understand and quantify ecosystem services.

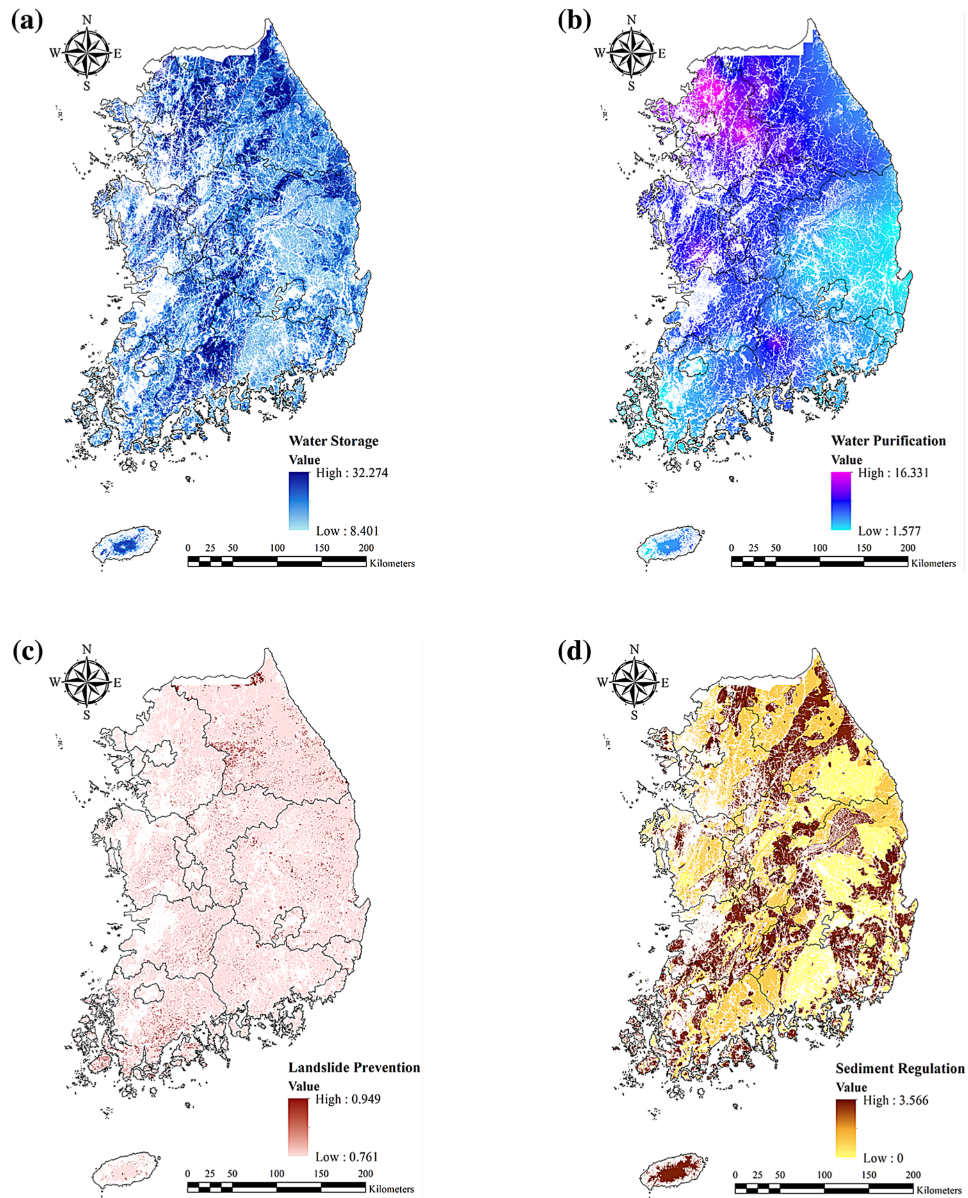

Fig. 3 Four forest ecosystem functions that deliver the services quantified in South Korea: **a** water storage capacity in forest soil for water storage service; **b** reduced suspended sediment for water purification service; **c** reduced soil erosion for landslide prevention service, **d** reduced sediment yield for sediment regulation service

Table 6 Comparison of quantifications (national average units per ha). *Source*: [a] KFS (2007), [b] KFS (2010), [c] GFERI (2014)

Service category	Ecosystem functions for the services	This study	Kim et al. (2012)	Other estimates
Water storage	Water storage capacity in forest soil	2142 t/ha	2734 t/ha	2857 t/ha[a]
Water purification	Reduced suspended sediment	608 kg/ha	151 kg/ha	600 kg/ha[b]
Landslide prevention	Reduced soil erosion	77 m^3/ha	76 m^3/ha	80 m^3/ha[c]
Sediment regulation	Reduced sediment yield	285 m^3/ha	289 m^3/ha	292.2 m^3/ha[c]

Ecosystem services quantification and mapping are useful for making sustainable decisions on managing trade-offs, such as uncertainties and land use planning. To support ecosystem-based management policy, we assessed indicators based on unit area using GIS. This helps decision makers to identify sites where high densities ecosystem

Table 7 Quantification result by forest type

Classification	Water storage capacity in forest soil (t)	Reduced suspended sediment (kg/ha)	Reduced soil erosion (m^3/ha)	Reduced sediment yield (m^3/ha)
Forest type				
Coniferous	4,961,659,251	1,438,649,197	185,650,464	689,864,660
Broadleaf	3,942,561,732	997,336,202	114,997,300	429,995,704
Mixed	3,193,726,562	1,003,741,788	131,067,222	492,871,101
Total	12,097,947,545	3,439,727,187	431,714,986	1,612,731,465

services are distributed. Thus, these quantification and spatial distribution results will support decision-making and planning according to the potential benefits and losses of natural environments.

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