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A GIS-based approach for quantifying and mapping carbon sink and stock values of forest ecosystem: A case study

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Abstract

This paper explored a GIS-based approach for quantifying and mapping economic values of carbon sink and stock of forest ecosystem. The approach highlighted use of GIS to develop database, perform spatial analysis and map economic values. And it was applied to a case of Tiantai County in Zhejiang Province of southeast China, for quantifying and mapping the values of vegetation carbon sink (VCS_i), vegetation carbon stock (VCS_t) and soil carbon stock (SCS) of forest ecosystem. By integrating forest inventory data and soil inventory data into GIS, vegetation photosynthesis method combined with forest biomass method and stem volume method were employed to quantify the VCS_i and VCS_t, and soil type method was applied to calculate the SCS. The selected carbon sink value and carbon stock values in the case area were mapped as data layers in GIS after gridding process, with each layer containing monetary values for every 25m cell. Results showed that the economic values of VCS_i, VCS_t and SCS of the case were approximately 895.26 million Yuan, 1369.40 million Yuan, 9303.21 million Yuan, respectively, and each value was spatially heterogeneous for the case. Depending on spatial maps of carbon sink and stock values, the suggestions and implications for improving carbon sink and stock are extensively discussed.

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Keywords: vegetation carbon sink (VCS_i); vegetation carbon stock (VCS_t); soil carbon stock (SCS); geographic information system (GIS); forest ecosystem;

1. Introduction

Climate change is the leading ecologic, economic and geopolitical issue of the 21st Century and has even the potential to rewrite the global equation for prosperity, development and peace. Since the late

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1980s, global warming has increasingly caused extensive concern of the international community. To mitigate greenhouse effects, it is essential to provide managers and policy makers with accurate information on the current state, dynamics, and spatial distribution of carbon sources and sinks [1]. Forest ecosystem, as a huge carbon pool, has been also proposed as a means to reduce net greenhouse gas emissions, by either reducing CO_2 sources or enhancing sinks [2]. Forest carbon sink and stock would be possible to substantially offset the industrial emissions of carbon dioxide by expanding the forest areas [3]. Globally, the terrestrial ecosystem stores about 2477 billion tons carbon and 1150 billion tons are stored in the forest vegetation (19%) and soil (81%) [4]. Forest vegetation acts as a sink for CO_2 by fixing carbon during photosynthesis and storing excess carbon as biomass [5]. Meantime, soil system as a bigger carbon pool holds four times more carbon than vegetation carbon pool [4]. Therefore, quantifying and mapping economic values of carbon sink and stock of forest ecosystem are essentially needed for the following carbon trading and forest carbon projects. Over the past twenty years, several studies have analyzed the potential impact of forest carbon sink and stock by estimating their capacity in a variety of settings [2,6-7]. However, one common challenge is to map spatial patterns and distribution of forest vegetation and soil carbon, and their values. So far, GIS-based spatially explicit approaches have been developed for producing geo-referenced estimates of carbon sink and stock potential [8-9], and GIS is usually employed to process model inputs (land cover, soil texture) and to visualize results [9-10]. However, few studies fully integrate process-based models with GIS to estimate carbon sequestration of terrestrial ecosystems and to conduct land-use planning spatially [11]. In the near future, the forest carbon markets may require spatially explicit patterns of forest carbon sink and stock values at various scales [1]. Therefore, there is an urgent need to apply GIS technique to demarcate carbon pool unit of forest ecosystem and their values on the map, and it will provide a foundation for managers to identify where is more essential to be focused.

In this study, a GIS-based approach for quantifying and mapping economic values of carbon sink and stock of forest ecosystem was built. Depending on the GIS platform, photosynthesis method combined with forest biomass method and stem volume method were employed to quantify volume of vegetation carbon fixation and stocks, and soil type method was applied to calculate the volume of SCS for Tiantai County in Zhejiang province of southeast China. Our specific objective is to highlight GIS research avenues to integrate the forest inventory data, soil inventory data into GIS to quantify and map the carbon sink and stock values of forest ecosystem.

2. Definition of forest ecosystem carbon sink and stock

Forest carbon sink, here vegetation carbon sink, mainly refers to capability and volume of vegetation fixing atmospheric CO_2 [12]. In this paper, we solely define the VCS_i as carbon sequestration from the atmosphere. Accordingly, forest carbon stock mainly includes vegetation carbon stock, soil carbon stock, litter carbon stock and animal carbon stock [4,13]. VCS_t is the carbon content that above-ground vegetation holds. SCS refers to carbon content that soil organic matter (e.g. soil humus) holds. Researchers have made lots of assessments for soil carbon storage, especially in the forest ecosystem or agricultural ecosystem. They found out that during the period of 1981~2000, the vegetation carbon storage of Chinese forest ecosystem is estimated at 1.58PgC, while the soil carbon storage in forest ecosystem is 1.41PgC [14]. Thus soil system is regarded as the largest carbon pool. Litter carbon stock refers to carbon amount that litters hold, it varies with different temperature and humidity. For instance, in the dry cold zone the litter is degraded slowly, and carbon stock amount is large. On the contrary, in wet warm zone the litter is degraded fast, and carbon stock amount is small. Because most of litters as humus are ultimately stored in the soil, the litter carbon stock is party of soil carbon storage, and it is not estimated in order to avoid the double counting in the study. Animal carbon stock accounts for a little proportion of the forest ecosystem carbon stocks [13, 15], so estimate for it is neglected in this study.

Therefore, VCS_i, VCS_t and SCS dominate in forest ecosystem, and become our research emphasis for valuation and mapping.

3. Case study

3.1. Site descriptions

Tiantai County is located at the east of Zhejiang Province, People's Republic of China (120°41′–121°16′ E, 28°57′–29°21′ N) with 54.7 km in length of EW and 33.5 km in width of SN, covering an area of 1423.8 km^2. The county is politically administrated by three urban districts, twelve rural towns, five forestry centers and a national forest park. It is a typically hilly area controlled by subtropical monsoon climate, combined with average annual temperature and rainfall of 16.8 ℃, 1450 mm, respectively. Here we emphasize that there exists five soil types and twenty four soil genera. And red soils dominate up to 63% of the total area, and the rest includes paddy soils (15.54%), yellow soils (14.19%), lithologic soils (3.7%) and fluvo-aquic soils (3.58%). Forests, arable land, open water and others amount up to 66.9%, 22.2%, 2.8% and 8.1% of total area in the county, respectively. High forest cover (66.9%) leads to 192.7 ha stumpages volume of woods, which were dominated by coniferous forest (91%), coniferous–broadleaf mixed forest (7.4%), and broadleaf forest (1.6%) in the Tiantai County.

3.2. Database development and approach application

Evaluating and mapping the carbon sink and stock values of forest ecosystem relies on a multi-source database. The needed data mainly involves some statistical data, e.g. forest inventory data, soil inventory data.Table 1 provides details of the database developed.

Table 1. Multi-source database developed for evaluating and mapping carbon sink and stock values

Data	Resolution/Scale	Data source	Description
DOM	2.5 m	Bureau of Surveying and Mapping, Zhejiang Province	SPOT satellite image
DEM	25 m	Bureau of Surveying and Mapping, Zhejiang Province	Elevation, slope gradient, and slope length
Land use	1:50 000	The Bureau of Land Resources, Tiantai County	Land use and land cover categories
Forest	1:50 000	The Bureau of forest, Tiantai County	Forest categories, vegetation types
Soil	1:200 000	The Bureau of Agriculture, Tiantai County	Soil physical properties e.g. texture, bulk density, etc.

For valuation, the DEM was prepared after running mosaic tool and clipping based on the layer of municipal borderline [16]. The papery land use map (1:50,000), forest resource map (dominant species) were digitized as vector format and projected to the same coordinate system (Beijing 54). The DOM was used for adjusting the land use/land cover layer. The valuation results were mapped as raster format with 25m cell size, and the total forest carbon sink and stock values were presented as RMB (Chinese currency, 6.831 Yuan=US$1 as of 2009). ArcGIS 9.2, ArcView GIS 3.3 (ESRI Inc.) and MapInfo Professional 7.5 (MapInfo inst.) were used for data compilation, surface analysis and statistical work.

The map of forest species (e.g. pine, cypress, Chinese fir, bamboo grove, broadleaf forest, mixed woods, etc.) and/or satellite imagery is original data to be interpreted to a forest resource map (forest layer) by the use of remote sensing technique and GIS tools [16]. We extract five vegetation types from forest layer, say wooden land (such as pine, cypress, Chinese fir, bamboo grove, economic forest), shrub land, open forest land, afforestation land and forest grassland, to create a "vegetation layer" (V layer) with some attribute fields such as "area", "vegetation type" , "stem volume", "vegetation biomass", "NPP" and "VCS_t density" etc. Analogically, 24 soil genera are extracted from the vectorized soil distribution map to create a soil layer (S layer) with some attribute fields such as "soil area", "soil type", "soil genera" and "soil carbon density", etc. The V layer and the S layer are stored in GIS, and the GIS-embodied database is built for further analysis.

4. Methodologies

A GIS-based technical framework and four key steps of evaluating and mapping the carbon sink and stock values of forest ecosystem are illustrated as Fig.1. Four steps are as follows: Step 1 (identification of study area) emphasizes a specification of the boundaries and scopes the core items to be valued. Step 2 (data collection and database development) provides a data basis for valuation and spatial analysis. Step 3 (material amount estimation) estimates the material amount of VCS_i, VCS_t, and SCS by integrating mathematic models with GIS. Based on material amount, Step 4 (valuation and mapping) evaluates the carbon sink and stock values of forest ecosystem using environmental economics methods (e.g. reforestation cost method and carbon taxation method), and highlights spatial visualization by means of GIS. Further details of valuation approaches are discussed below.

4.1. VCS_i and VCS_t estimate approach

As elucidated above, VCS_i mainly involves forest CO_2 fixation. In forest ecosystem, plants transform solar energy into biotic energy through photosynthesis, fixing CO_2 and releasing O_2, and mitigating greenhouse gases increase, and it plays an irreplaceable role in maintaining the CO_2/O_2 balance. Based on the forest inventory data, in this study we adopted the photosynthesis method associated with vegetation NPP. NPP, a key component of the terrestrial carbon cycle, represents the net carbon accumulation by the stand and accounts most of the annual carbon fluxes between the atmosphere and biosphere [18-19]. The formula of photosynthesis is as follows:

$$CO_2(264g) + H_2O(108g) \rightarrow C_6H_{12}O_6(180g) + O_2(193g) \rightarrow Amylase(162g) \quad (1)$$

As shown in the Eq. (1), plants absorb 6772cal solar energy and 264 g CO_2 for producing 193g O_2 and 162g dry material stored as fibre and starch in the plants [17]. And at a molecule level, the ratio of carbon, hydrogen and oxygen of vegetation fibre is 1.5:2:1, and most trees keep the same ratio [20]. On the basic of relative atomic mass of carbon, hydrogen and oxygen, we estimate that the VCS_t density equals to half of the forest biomass volume [21-22]. In this study, a ratio of 0.5 is used to convert biomass to VCS_t density [22]. Using the method, we can estimate material amount of atmospheric CO_2 fixation, and calculate the VCS_t amount of Tiantai County. The equations are shown below:

$$M_{VCSi} = 1.63 \times \sum_i S_i \times NPP_i \quad (2)$$

$$M_{VCSt} = \sum_i S_i \times D_{CSD_i} \quad (3)$$

$$D_{CSD_i} = B_i \times 0.5 \quad (4)$$

Where M_{VCSi}, M_{VCSt} are the amounts of VCS_i ($t.a^{-1}$) and VCS_t ($t.a^{-1}$), respectively; S_i is the area of the $i$thvegetation type (hm^2); NPP_i is net primary productivity value of the ith vegetation type ($t.hm^{-2}.a^{-1}$); D_{CSDi} ,B_i are the carbon stockdensity and biomass of the ith vegetation type ($t.hm^{-2}$), respectively.

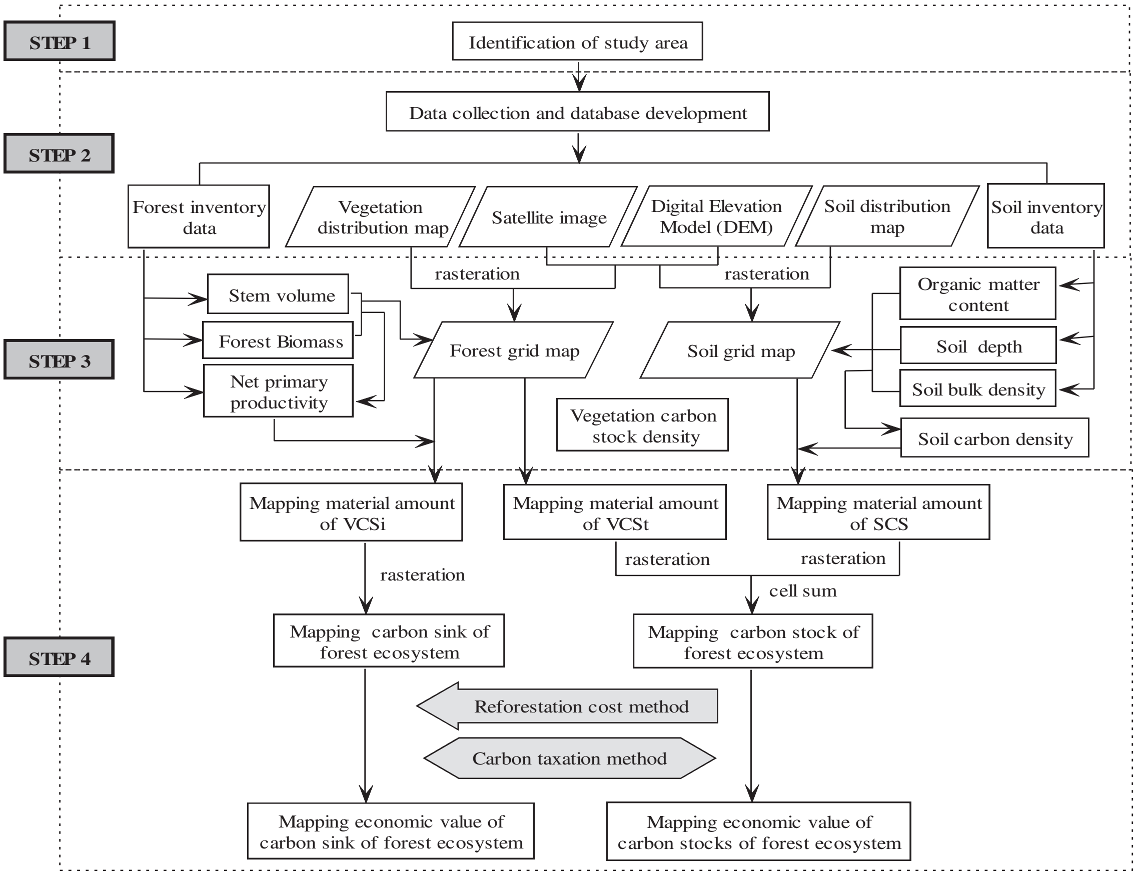

Fig.1. Technical framework for mapping economic values of carbon sink and stock

In this study, depending on the forest inventory plot data (2009) and forest statistics data of Tiantai County (forest bureau, 2009), we apply variable biomass expansion factor (defined as the ratio of all stand biomass to stem volume) method [4,22-23] to calculate the forest biomass. According to the forest inventory data, for the forest land, the dominant trees are pine (62.57%), Chinese fir (8.26%), and Cypress (6.79%). And bamboo grove (10.22%), economic forest (3.16%), Shrubs (4.07%), and open forest (2.67%) account for great fraction of the total forest land. Given that different plants have different NPP and carbon storage capability, we apply Fang's approaches and Sun's approaches to estimate the NPP and carbon stock density of different vegetation type, shown in Table 2 [23]. Depending on the biomass method and stem volume method, the stem volume is calculated from forest inventory data and then converted to forest biomass using biomass conversion equations [22-25], further the VCS_t density and NPP value (see Table 2) are estimated by NPP calculation formula and Eq. (3,4). Another, for the wooden forest, NPP value is the mean value of the six NPP estimates of pine, cypress, Chinese fir, bamboo grove, economic forest and other wooden forest. Otherwise, because of the insufficient data of afforestation land and forest grassland, their biomass and carbon stock density is not considered in the study. And then all the data items are input into the V layer as attributes in GIS.

Table 2. NPP estimates of different forest vegetation types for Tiantai County

Forest type	Forest species	NPP estimate formula	Forest biomass (x) (t.hm^{-2})	NPP value (y) (t.hm^{-2}.a^{-1})	Carbon stock density(t.hm^{-2})
Wooden forest	Pine	$y=5.565x^{0.157}$	24.656	9.205	12.328
	Cypress	$1/y=12.092/x+0.048$	23.542	2.575	11.771
	Chinese fir	$y=-0.018x+9.059$	35.251	8.635	17.626
	Bamboo grove	$y=10.78$	57.596	10.78	28.798
	Economic forest	$y=9.2$	23.700	9.2	11.850
	Other wooden forest	$y=0.208x+1.836$	12.769	4.492	6.385
Shrub forest	Mulberry, Tea and other shrubs	$1/y=1.27/x^{1.196}+0.056$	19.760	10.892	9.88
Open forest	—	$1/y=1.27/x^{1.196}+0.056$	11.783	8.166	5.892
Afforestation land	—	$y=5.93$	—	5.93	—
Forest grassland	—	$y=1.16$	—	1.16	—

Where y is the estimate of NPP value; x is the forest biomass volume.

4.2. SCS estimate approach

As mentioned before, SCS is an essential component of the global carbon cycle [26]. Soil organic carbon (SOC) is the largest terrestrial carbon pool, and SOC in active exchange with the atmosphere constitutes approximately two-thirds of the carbon in terrestrial ecosystems [27]. Organic matters are the dominant carbon morphology in soil, so we often as a substitution of estimating SCS. In this study, we utilize the soil type method [26] to estimate SCS stock. Our calculations incorporate layer data to 1- meter depth, because the 0- to 1- meter layer is thought to include most of the SOC mass in a soil column [29]. Firstly, we calculate the SOC density, which represents the weight of organic carbon in the 1m^3 soil-cubic at the soil profile depth of 1.0 meter. And the SOC density varies with soil genus. Secondly, we transfer the SOC density into soil carbon density. The chemical components of SOC are complex, involving a wide array of organic constituents [30], but we can use the Bemmelen factor to estimate the quantity of carbon [31]. Finally, we input the soil carbon density value to the Field map of soil genera (e.g. red clay, yellow sand, zisha clay) in GIS, then multiple the soil carbon density by the area of each soil polygon to estimate the amount of SCS over the region. By means of GIS, spatial distribution of SCS is mapped for further analysis.

The equation of soil carbon density estimate is as follows:

$$D_{SCD_i}=\overline{\rho}\times P_{SOC_i}\times B_f \quad (5)$$

Where D_{SCDi} is the soil carbon density of the ith soil genera (kg.m^{-2}); ρ is the average bulk density of soil (kg.m^{-3}); P_{SOCi} is the percentage of organic matters of the ith soil genera (%); B_f is the Bemmelen factor (0.58).

The relation of SCS estimate is as follows:

$$M_{SCS}=\sum_i D_{SCD_i}\times A_i \quad (6)$$

Where M_{SCS} is the amount of SCS; Ai is the area of the ith soil genera (m^2);

Table 3. Soil carbon density of different soil genera

Soil type	Soil genera	Area (km^2)	Soil carbon density ($kg.m^{-2}$)
Fluvo-aquic soils	Alluvial sediment soil	24.339	3.924
	Silt soil	20.411	3.953
	Free sand	6.227	1.026
Red soils	Shiraiwa sand	9.369	2.433
	Pink clay	442.278	2.226
	Red soil	5.067	2.798
	Red sand	12.680	3.277
	Red clay	10.604	3.19
	Yellow red earth	2.590	2.65
	Yellow mud bars	3.994	1.74
	Yellow soil	351.275	5.498
	Red sand clay	68.008	4.235
Yellow soils	Mountain yellow soil sediment	94.222	12.849
	Mountain yellow earth	97.168	27.475
Paddy soils	Red clay field	2.922	5.944
	Alluvial sediment field	25.683	6.153
	Yellow sediment field	33.133	10.715
	Yellow sand field	34.941	5.756
	Yellow bars paddy	95.544	4.468
	Sediment field	22.138	6.216
	Mountain yellow sediment field	6.905	10.728
Lithologic soils	Purpurin sand	18.344	5.09
	Purple soil	33.759	4.735
	Brown clay	0.594	10.901

According to the 2nd soil inventory data of Tiantai County, we determine the percentage of soil organic matters in different soil layers from 0- to 1- meter depth for each soil genera. Relying on the soil inventory data, we determine the average soil bulk density as $1200 kg.m^{-3}$ in Tiantai County. And the soil carbon density of different soil genera is calculated (see Table 3). And then all the data items are input into the S layer as attributes in GIS.

4.3. Valuation and mapping

In this study, reforestation cost method and carbon taxation method are applied to estimate the VCS_i price. The mean value calculated by the two methods is approximately estimation of VCS_i price. Similarly, Carbon taxation method is solely employed to estimate the price of VCS_t and SCS. Depending on Ouyan's method and Price index method [32], we determine that the reforestation cost of carbon is 492.9 $Yuan.t^{-1}$ in 2009, the carbon tax rate in Sweden is 1025 $Yuan.t^{-1}$. Based on methods above, the VCS_i price is 758.95 $Yuan.t^{-1}$, the VCS_t price and SCS price are the same, 1025 $Yuan.t^{-1}$.

We determine and map material amount of VCS_i, VCS_t, and SCS in different land polygons, depending on the V layer and the S layer in GIS-embodied database and "raster calculator" tool of GIS with Eq. (2, 3, and 6). Then they are named as some new layers, say "VCS_i layer", "VCS_t layer" and "SCS_t layer". And then they are rasterized as grid layers, respectively. Meantime, the corresponding carbon prices estimated are input to "V layer" and "S layer" as attribute field in GIS, and two "Price layers" (named as P_1 layer and P_2 layer respectively) contained the carbon sink and stock price. All the layers were presented in raster format as the same cell size (25m cell), with each layer containing monetary values for every 25m cell. Then we multiply the "VCS_i layer" by the P_1 layer in GIS map calculator, the VCS_i value is distributed to each cell and the economic value of VCS_i is spatially mapped. Analogically, we multiply the "VCS_t layer" and the "SCS_t layer" by the P_2 layer in GIS map calculator, respectively. After that, the economic value of VCS_t and SCS are spatially visualized and mapped. Relying on "cell statistics" of GIS, we quantify the total economic values of VCS_i, VCS_t, and SCS of forest ecosystemin Tiantai County.

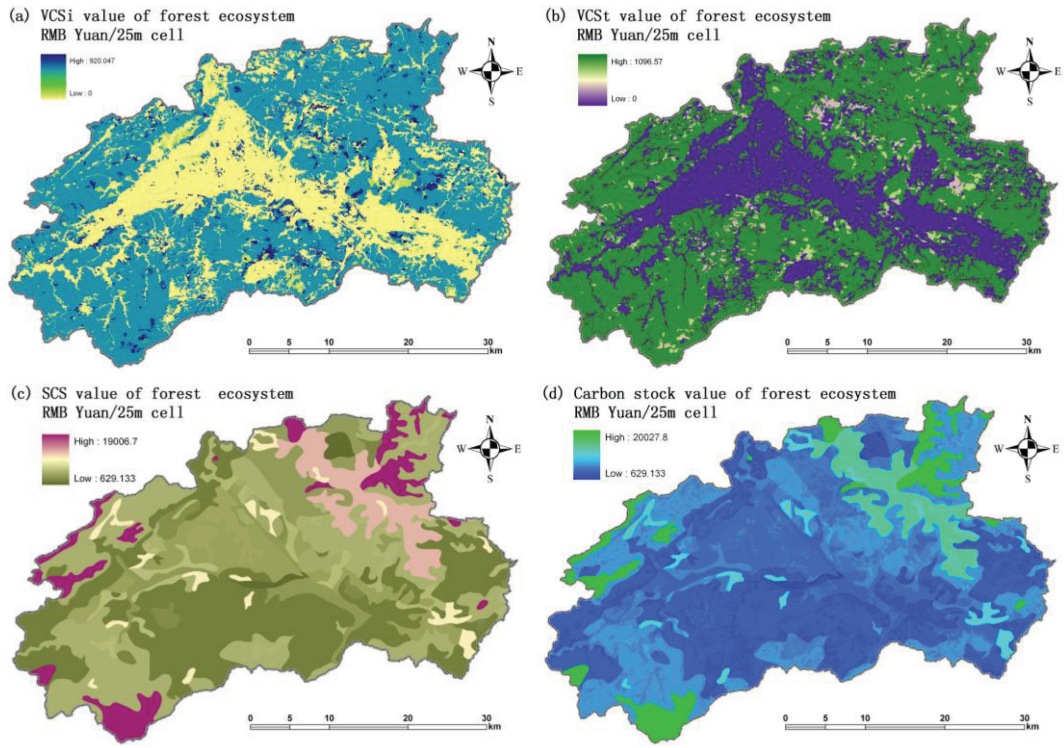

Fig.2. (a) Mapping the economic value of VCS_i; (b) Mapping the economic value of VCS_t; (c) Mapping the economic value of SCS; (d) Mapping the total carbon stock value of forest ecosystem in Tiantai County.

5. Results and discussions

Spatial heterogeneity of sink and stock values of forest ecosystem in Tiantai County have been shown in Fig.2. By the use of "cell statistics" of GIS, we estimated the material amount of VCS_i, VCS_t and SCS provided by the Tiantai County to be approximately 1.18 million tons, 1.34 million tons and 9.08 million tons, respectively. The amount of soil carbon stock was nearly 3.61 times more than that of forest carbon sink and stock, the ratio approaches the ratio of the soil carbon stock to forest carbon stock at global scale [4]. And the corresponding economic values of VCS_i, VCS_t and SCS are 895.26 million Yuan, 1369.40 million Yuan, 9303.21million Yuan respectively, and each value was spatially heterogeneous for the case (see Fig.2). This shows that Tiantai County has a huge potential for carbon trading and following carbon sink programs. Cell statistical data indicated that the VCS_i value varied from 0 to 920.05 Yuan for each 25 m cell.Typically, the north eastern and southwest hilly areas with high vegetation cover have a greater carbon sink value, especially for the four forest farms and the national forest park, where trees and bamboo groves mainly distribute. Some regions have few, even no carbon sink values (Fig.2a), especially for the mid-part of the Tiantai County ("Y" shape) where most are arable land and land for construction use with low forest cover. The VCS_t values vary from 0 to 1096.57 Yuan for each 25m cell. Spatial distribution of VCS_t values are similar with that of VCS_i values (see Fig.2b). The spatial distribution of SCS values is shown in Fig.2c. SCS values vary from 629.13 to 19006.7 Yuan for each 25m cell. The heterogeneity is ascribed to the difference in organic matter contents of different soil type. In the case, the order of the organic matters content is yellow soils > paddy soils > lithologic soils > red soils > fluvo-aquic soils, so the spatial distribution of SCS values is positive correlative with the soil distribution (see Fig.2c). From the results, we conclude that soil carbon stock values constitute a high proportion (80.42%) of the total carbon values, so the spatial distribution of total carbon stock values are similar with that of SCS values (see Fig.2d).

Based on the results, some concrete suggestions for improving carbon sink and stock for local forest ecosystem-based carbon management are discussed below.

(i) The high forest cover of the Tiantai County should be maintained and protected. Tiantai County is an under-developed region, strong drive of economic development has brought pressure on the forest ecosystem. So the huge forest volume should be kept and made full use of during economic development. Over-logging timber stands must be banned for keeping the carbon pool stable, and more efforts should be exerted to prevent forest fire, pest and illegal occupancy. Reforestation and afforestation are also regarded as a win–win strategy for the cutting blanks [10].

(ii) Management on forest resources should be enhanced. Forest stands should be diversified and improved. Trees in the different life phase hold different capability of carbon sink and stock. So choosing the tree species (such as pine, fir, camphor and bamboo, etc.) which hold higher capability of carbon fixation, and renewing matured trees reasonably will be conducive to raise the capability of carbon sink and stock of forest ecosystem. Meantime, management scenarios that involve transferring from mainly timber-oriented forest to multi-functional forest should be made for carbon sink diversification [33].

(iii) Soil resource conservation should be further emphasized. More efforts must be concentrated on the prevention of the soil loss, especially for the yellow soils and paddy soils with high organic matters. Local government needs concern on the forestland soil maintenance and soil organic carbon stabilization.

6. Conclusion

With GIS techniques and valuation approaches, we presented a GIS-based approach for quantifying and mapping carbon sink and stock values of forest ecosystem at the county level. The approach integrated the forest inventory data, soil inventory data and GIS tool through quantitative models such as NPP calculation model, biomass model, etc. The advantages of GIS-based approach are its simplicity, low cost, and estimation of spatially explicit patterns and temporal-spatial dynamic prediction of forest carbon. From the valuation results of the case study, the GIS-based approach is feasible and reasonable. Meantime, the economic values of three selected carbon sink and carbon stocks are spatially heterogeneous, which helps to determine a proposed alternatives of forest ecosystem carbon management in the critical areas. However, given the temporal-spatial variability of the variables and parameters of forest and soil, the uncertainties from sampling, measuring, variation of the variables and parameters, interactions between them, reduce the accuracy of the results. Nevertheless, it is not a crucial problem for this paper whose main purpose is more to present an application of a GIS technique than providing exact and completely reliable data on the value of the items assessed. Although we limited the use of GIS to quantify the allocation of carbon sink and stock values of forest ecosystem at county level, this can be an important research avenue to provide a GIS-based framework for valuation and mapping at provincial or national scale.

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