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SPECIAL ISSUE: The Dynamics and Value of Ecosystem Services: Integrating Economic and Ecological Perspectives

Evaluating scale dependence of ecosystem service valuation: a comparison of NOAA-AVHRR and Landsat TM datasets

Keri M. Konarska *, Paul C. Sutton, Michael Castellon

Department of Geography, University of Denver, Denver, CO 80208, USA

Abstract

The purpose of this study is to determine how the spatial scale of measurement influences ecosystem service valuation. Two land cover datasets were compared: one classified from 1-km imagery and one classified from 30-m imagery. The coarse resolution biome dataset used in this study (called the International Geosphere Biosphere Programme (IGBP) Dataset) was classified from 1-km NOAA-AVHRR imagery and includes 17 biome types. The finer resolution National Land Cover Dataset (NLCD) used in this study was classified from 30-m Landsat Thematic Mapper imagery and has 21 land-cover classes. A common land-cover classification scheme containing eight land-cover types was developed in order to compare the two datasets. The areal extent of these land-cover types in each dataset was determined and then multiplied by the value of the ecosystem services to arrive at a total value for ecosystem services. Generally, the areal extent of Lakes/Rivers, barren areas, urban areas, and wetlands in the NLCD showed the largest increases when compared to their extents in the IGBP dataset. The total value of ecosystem services for every state except New Mexico increased using the NLCD. The total value of ecosystem services for the conterminous US increased by almost 200%. The total value according to the 1 km resolution IGBP data was 259 billion/yr whereas the total value according to the finer resolution (30 m) NLCD data was over $773 billion/yr. Most of the increase in ecosystem service value can be attributed to the increased extent of wetlands in the NLCD. It is also interesting to note that the total value of ecosystem services in the conterminous US is only 8% of gross domestic product of those states ($8.6 trillion). These methods use land cover as a proxy measure of ecosystem service. Some of the pitfalls and promise of this assumption are discussed in the context of spatially explicit remotely sensed image data. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Ecosystem service value; Scale dependence; NLCD; IGBP

1. Introduction

Ecosystems around the globe create and maintain an environment suitable for the continuation of human life. Ecosystems supply goods such as timber, pharmaceuticals, and seafood, and also provide services including purification of air and water, stabilization of climate, and generation and renewal of soil and soil fertility (Daily, 1997). However, most ecosystem services exist outside commercial markets, and thus have little effect on policy decisions. Calculating the value of ecosys-

* Corresponding author. Tel.: +1-303-871-2399

E-mail addresses: kkonarsk@du.edu (K.M. Konarska), psutton@du.edu (P.C. Sutton), mcastell@du.edu (M. Castellon).

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tem services may improve economic efficiency, provide metrics for decision-making, and provide the impetus to preserve the ecosystems that provide the most valuable services.

The development of a standardized framework for making comprehensive assessments of ecosystem functions, goods, and services is one of the challenges addressed in this special issue (De Groot, 2002). '*…data on ecosystem goods and services often appears at incompatible scales of analysis and is classified differently by different authors*'. This paper addresses specific examples of the scale and classification problems by comparing two remotely sensed images of the conterminous US that were measured at different spatial resolutions (30 m, and 1 km) and were classified differently (Andersen Level II, and biomes of the International Geosphere Biosphere Program (IGBP)). Remotely sensed imagery with global coverage is increasingly available at finer spatial, spectral, and temporal resolutions. Consequently, satellite imagery is probably an important information source for assessing and monitoring ecosystem services. This research attempts to explore some of the potential and limitations of using remotely sensed imagery for assessing ecosystem services. A fundamental premise of this work is that land cover is a proxy measure of ecosystem service.

In 1997, Costanza and co-authors attempted to place a total value on the Earth's ecosystem services. Costanza et al. (1997) calculated the total area covered by 17 biomes classified by Bailey. For each biome, the services provided by the ecosystem were identified and given a monetary value based on previous studies and original calculations. The value of Temperate Forest was estimated as \$302 ha^{-1} yr^{-1}; Wetlands received a value of \$14,785 ha^{-1} yr^{-1}; Grasslands received a value of \$232 ha^{-1} yr^{-1}; Lakes/Rivers had an estimated value of \$8498 ha^{-1} yr^{-1}. The estimated value per hectare of each ecosystem (the total of all ecosystem services) was then multiplied by the areal extent of each biome to find the total monetary value of the ecosystem. The total value for global ecosystem services was estimated as \$33 trillion/yr (Costanza et al., 1997).

Classified satellite imagery allows for the measurement of the areal extent of distinct land-covers and the use of aggregate areal extent to calculate total ecosystem value using the aforementioned figures. This admittedly crude method of valuation is a legitimate first step and will undoubtedly be improved upon in many ways. Remotely sensed imagery is useful in that it can be used to identify ecosystem functions, goods, and services in a spatially explicit manner. Another distinct challenge identified by Farber et al. in this issue is the problem of appropriately valuing these functions, goods, and services (Farber et al., 2002). The spatially explicit nature of the imagery allows for several improved methods of ecosystem service valuation.

The distance of the ecosystem to a population center, the fragmented nature of many ecosystems, the purchasing power of people in various parts of the world, and the spatial scale at which the ecosystem extent is measured, all can influence the valuation of ecosystem services. While all of these observations are valid, perhaps the easiest to quantify is the effect that scale of measurement may have on the total ecosystem service value. For example, scale may also have an effect on the relative value each state contributes to the total ecosystem service value for the US. Maine may contribute 10% of the US total ecosystem service value at a coarse scale and 20% of the US total ecosystem service value at a finer scale. Relative values may be variable with scale, which can complicate comparisons and indicates that relative valuations made at one scale will not be the same when measured at another scale.

Scale is important to researchers attempting to identify and explain observable patterns (Gibson et al., 2000). Yet, the scale of measurement used in a study is rarely reported, nor is the issue of scale routinely addressed (Atkinson and Tate, 2000; Gibson et al., 2000; Meentemeyer, 1989). This may be due to ambiguity of the term scale. Scale can refer to either the amount of detail or the spatial extent of a map (Goodchild and Proctor, 1997). In addition to the spatial characteristics of an event, Gibson et al. (2000) include the temporal, quantitative, and analytical dimensions used to study the problem in their definition of scale. For the purposes of this study, we use scale to represent the spatial resolution of the remotely sensed imagery that was classified to create land-cover datasets.

Research regarding the factor of scale in remotely sensed datasets has shown that increasing the pixel size of the image changes the amount of area covered by each land-cover class. The extent of fragmented land-cover types decreases as pixel size becomes coarser (Moody and Woodcock, 1994; Turner et al., 1989). Land-cover types that are found in clumps either disappeared slowly or were retained as the image was degraded from fine to coarse resolution (Moody and Woodcock, 1994; Turner et al., 1989). For example, conifer forests, which were present in large, contiguous patches, increased in extent as 30 m Landsat Thematic Mapper (TM) image was aggregated to 1020 m (Moody and Woodcock, 1994). The amount of conifers increased along the edges of the forest patches as the surrounding cover types are aggregated into the forest class as the pixel size increased (Moody and Woodcock, 1994). When the resolution has been degraded beyond the size of the small patches of cover types such as water, the areal extent of that class declines (Moody and Woodcock, 1994).

The increased extent of fragmented ecosystems found in finer resolution datasets has direct implications for the valuation of ecosystem services, because the total value is dependent on the areal extent of land-cover types. Our research attempts to assess, measure, and discuss implications of the influence of measurement scale on ecosystem service value estimates for the conterminous US by comparing results using a coarse resolution dataset and a finer resolution dataset of classified remotely sensed imagery.

2. Data and methods

2.1. Coarse resolution (1 km^2): International Geosphere Biosphere Programme Dataset

The International Geosphere Biosphere Programme (IGBP) has overseen development of a global land-cover dataset containing seventeen biome classes, which is distributed by the US Geological Survey (USGS) EROS Data Center (Fig. 1) (Lauer and Eidenshink, 1998). The IGBP dataset is derived from geo-referenced National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA-AVHRR) imagery and classified into biomes by experts (Belward and Loveland, 1995). Land-cover maps derived from NOAA-AVHRR imagery are appropriate for analysis of large areas at small scales (Townshend and Tucker, 1984).

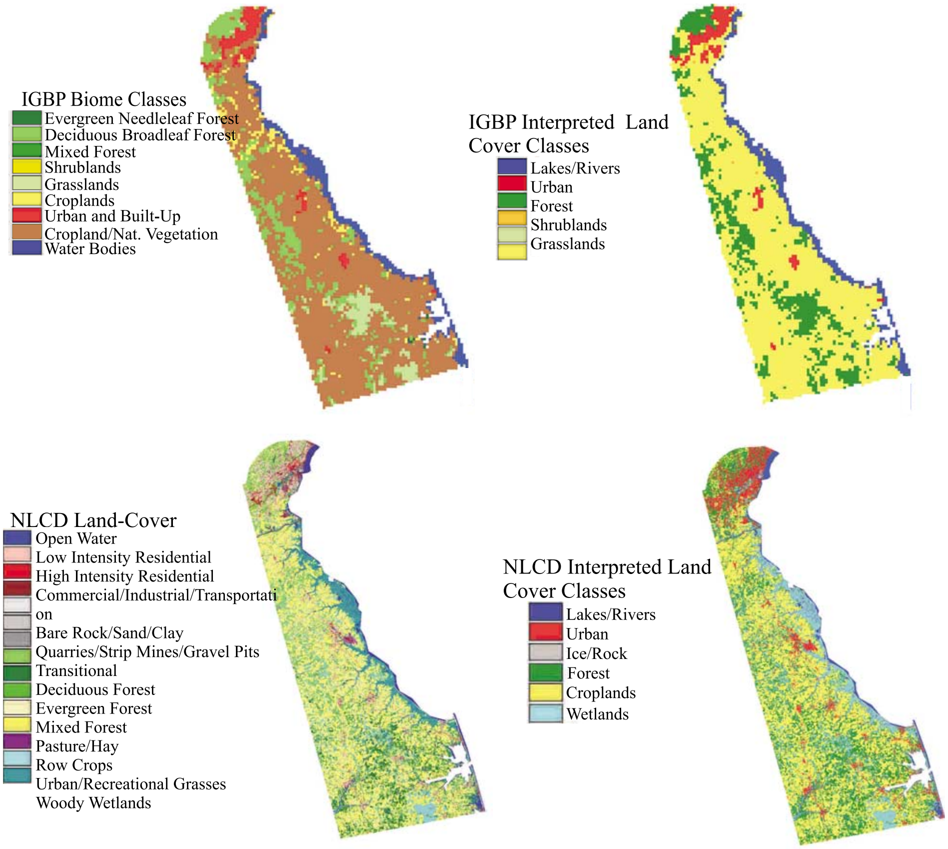
The 1-km IGBP dataset can be downloaded from the USGS EROS Data Center website (Global Land Cover Characterization Website, 2000). Each state included in this study was clipped out of the North American IGBP dataset and then reprojected to the matching Albers Conical Equal Area projection used for each state in the National Land Cover Dataset (NLCD).

2.1.1. Fine Resolution (30 m): National Land Cover Dataset

The fine resolution land-cover dataset that was used in this study was created as part of a cooperative project between the US Geological Survey and the US Environmental Protection Agency. This joint effort classified Landsat TM imagery, which has a resolution of 30 m, to produce a land-cover map for each state using a consistent land-use/land-cover classification scheme (Fig. 1). The NLCD is a continuous land-cover dataset for the conterminous US that includes 21 land-cover classes (Vogelmann et al., 2001, 1998a,b).

2.2. Aggregating the IGBP biomes and NLCD land-cover classes

As mentioned above, the IGBP dataset contains 17 biome classes while the NLCD includes 21 land-cover classes. A common classification scheme containing eight land-cover classes was created to facilitate comparison between the two datasets (Fig. 1). The eight interpreted classes in the common classification scheme were based on



IGBP Biome Classes	Land-Cover Classes and Ecosystem Service Values	NLCD Land-Cover Classes
Water Bodies	**Lakes/Rivers ($8,498 ha^{-1}yr^{-1})**	Open Water
Urban and Built-Up	**Urban ($0 ha^{-1}yr^{-1})**	Low Intensity Residential High Intensity Residential Commercial/Industrial/Transportation Urban/Recreational Grasses
Snow and Ice Barren or Sparsely Vegetated	**Ice/Rock ($0 ha^{-1}yr^{-1})**	Perennial Ice/Snow Bare Rock/Sand/Clay Quarries/Strip Mines/Gravel Pits Transitional
Mixed Forest Evergreen Needleleaf Forest Evergreen Broadleaf Forest Deciduous Needleleaf Forest Deciduous Broadleaf Forest	**Temperate Forest ($302 ha^{-1}yr^{-1})**	Deciduous Forest Evergreen Forest Mixed Forest
Closed Shrublands Open Shrublands Woody Savannas	**Shrublands ($267 ha^{-1}yr^{-1})**	Shrublands
Grasslands Savannas	**Grasslands ($232 ha^{-1}yr^{-1})**	Grasslands/Herbaceous
Croplands Cropland/Natural Vegetation Mosaic	**Croplands ($92 ha^{-1}yr^{-1})**	Orchards/Vineyards/Other Pasture/Hay Row Crops Small Grains Fallow
Permanent Wetlands	**Wetlands ($14,785 ha^{-1}yr^{-1})**	Woody Wetlands Emergent Herbaceous Wetlands

Fig. 1. The IGBP biome classes and NLCD land-cover classes were aggregated according to a general Anderson Level I classification scheme (Anderson et al. 1976). Ecosystem service values as given in Costanza et al. (1997) were applied to the aggregated classification scheme. The NLCD dataset has finer resolution, which is observable in the Delaware example.

the Anderson Level I classification system (Anderson et al., 1976). Ecosystem service values were then assigned to each common land-cover class according to the values used by Costanza et al. (1997). For example, barren areas covered with ice, snow, or rock receive an ecosystem service value of \$0/ha/yr; thus, all barren areas were included in one interpreted category called Ice/Rock. All urban areas were aggregated into one Urban land-cover category, which has an ecosystem service value of \$0/ha/yr. Temperate Forest also received one value (\$302/ha/yr) regardless of type of temperate forest, i.e. deciduous, evergreen or mixed. The interpreted Shrubland category (\$267/ha/yr) contains land-cover types characterized by the presence of some woody vegetation in addition to some grasses. Again, regardless of the type of crop grown in a certain area, the Cropland category received one ecosystem service value of \$92/ha/yr, so every agricultural land use class was included in one category. Two types of wetlands were identified during classification of the TM imagery: Woody Wetlands and Emergent Herbaceous Wetlands. These land-cover classes were included in one generalized Wetlands land-cover class, which was assigned a value of \$14 785/ha/yr.

2.3. Calculating the value of ecosystem services

Each cell in the IGBP dataset covers 1 000 000 m^2 of land on the Earth's surface. Thus, to calculate the total extent of each biome class, the number of cells in each biome class was multiplied by 1 000 000 m^2 and then converted to hectares. Each cell in the NLCD covers 900 m^2 of land on the Earth's surface. Thus, to calculate the total extent of each land-cover class, the number of cells in each land-cover class was multiplied by 900 m^2. The extent of the land-cover classes was then converted to hectares and summarized by interpreted ecosystem classes in order to utilize the ecosystem service values. The number of hectares in each land-cover class was multiplied by its corresponding ecosystem service value, taken from Costanza et al. (1997), to arrive at the total ecosystem service value for a particular land-cover type. The monetary values for the land-covers found in each state were summed to arrive at a total value for ecosystem services for each state.

3. Results

3.1. Comparing the areal extents of land-cover classes

When the NLCD was compared to the IGBP, the extent of Lakes/Rivers increased for 39 of the 48 states included in the analysis. Only the states bordering the Atlantic Ocean showed a decline in the amount of freshwater ecosystems found in each state. The NLCD dataset for each state included ocean water as part of the Open Water category; thus, the extents of Lakes/Rivers were inflated in coastal states. The pixels classified as ocean water were removed from the dataset because oceanic ecosystems should receive a different ecosystem service value than Lakes/Rivers. (In fact, marine resources account for approximately two-thirds of the world's total ecosystem service value.) Cells covering the Great Lakes were also removed from both datasets to facilitate comparison between the datasets: the IGBP dataset did not include the Great Lakes, whereas the NLCD dataset for those states did include some of the lakes as part of the Open Water category. Despite removing the Great Lakes from the analysis, the amount of area covered by Lakes/Rivers increased by approximately 56% for the conterminous US (Fig. 2).

The extent of areas covered by Urban increased for all states when calculated using the finer resolution NLCD dataset. Across the conterminous US, the amount of urbanized areas increased 113% (Fig. 2). Analysis of the NLCD dataset showed that the extent of barren areas covered by ice, snow, or rock increased for every state except Nevada where the extent of Ice/Rock declined by approximately 62%. Overall, the amount of Ice/Rock almost doubled when the NLCD values are compared to the extent of Ice/Rock found in the IGBP dataset (Fig. 2).

Within each state, Temperate Forest, Shrublands, Grasslands, and Croplands showed variable amounts of change between the datasets (Fig. 2). If the extent of one of these land-cover classes increased in the NLCD dataset, then another land-cover decreased in area. However, the majority of the states showed a decline in the areal extent of Grasslands and Shrublands. These land-cover classes showed a decreased extent in the NLCD dataset across the US in general (Fig. 2). The amount of Temperate Forest and Croplands increased in approximately half of the states included in the analysis. The amount of Temperate Forest varied little when its extent is considered across the conterminous US (Fig. 2). However, Croplands showed a 10% decrease in extent in the NLCD dataset as compared to the value found for the IGBP dataset (Fig. 2). This is probably due to the inclusion of the Cropland/Natural Vegetation Mosaic IGBP class as part of the Croplands interpreted land-cover class.

Wetlands showed the most dramatic increase as the areal extent of wetlands increased over 5000% when their total area was determined using the 30 m NLCD dataset (Fig. 2). According to the IGBP dataset, many states did not have any wetlands at all whereas the NLCD dataset identified wetlands in every state. In fact, every state showed an increased amount of wetlands in the NLCD dataset.

3.2. Comparing the ecosystem service values

All states except New Mexico showed an increase in the total value of ecosystem services when the areal extents of the land-cover classes from the NLCD dataset were used in the value calculation (Table 1). The total ecosystem service value for the conterminous US increased by 198% when calculated using the NLCD dataset (Table 1). Regardless of the dataset chosen, California, Florida, Louisiana, Maine, Minnesota, New York, and Texas have very high ecosystem service values and are ranked in the top fifteen for each dataset (Table 1).

The value of ecosystem services calculated using the IGBP dataset ranged from $278 million/yr in Rhode Island to almost $20 billion/yr in Texas (Fig. 3). Ecosystem service values calculated from the IGBP dataset show a relationship with the size of the state as the majority of states with values over $6 billion/yr are found in the western US (Fig. 3). Many of the small states in the northeast US have ecosystem service values of less than $2 billion/yr (Fig. 3). The coastal states from Virginia southward have similar ecosystem service values ranging from $4–6 billion/yr (Fig. 3). Ex-

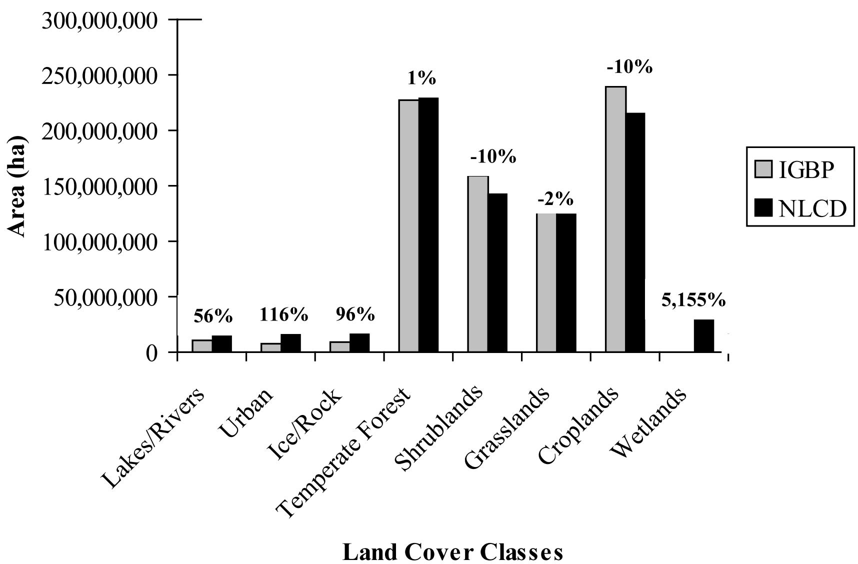


Fig. 2. Total area of each land-cover class in the conterminous US using each dataset. Lakes/Rivers, Urban, Ice/Rock, and Wetlands increased in extent when calculated using the 30-m dataset. Shrublands, Grasslands, and Croplands covered less area in the NLCD dataset as compared to their extents in the IGBP dataset. Temperate Forest showed little change in extent between the datasets.

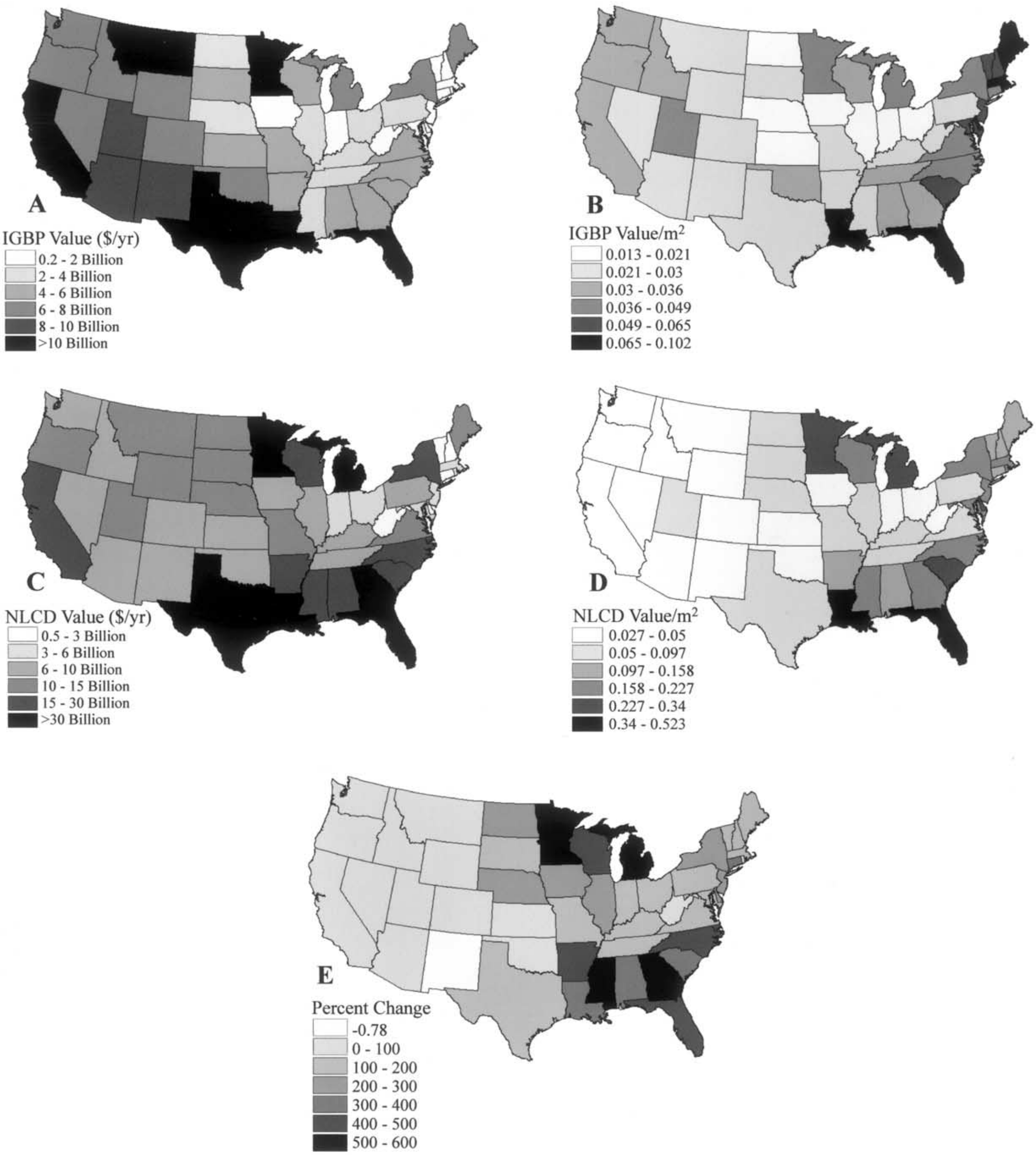


Fig. 3. Spatial distribution of ecosystem service values calculated for each state using the IGBP dataset and NLCD dataset: (A) Value of ecosystem services calculated using the IGBP dataset; (B) Value of ecosystem services per square meter determined using the IGBP dataset; (C) Value of ecosystem services calculated using the NLCD dataset; (D) Value of ecosystem services per square meter determined using the NLCD dataset; (E) Percent change as indicated by the amount the values calculated using the NLCD dataset differed from the values calculated using the IGBP dataset.

amination of ecosystem service values divided by the total area of the state in square meters showed that the states in the northeast US had a very high value per square meter, while states in the western US had relatively small ecosystem service values per square meter (Fig. 3).

Using the land-cover extents calculated from the NLCD dataset, ecosystem service values range from $500 million/yr in Rhode Island to over $75 billion/yr in Florida (Fig. 3). The majority of states with ecosystem service values over $15 billion/yr are found in the southeastern US and bordering the Great Lakes (Fig. 3). Many of the states with low ecosystem service values ranging from $0.5–3 billion/yr are found in the northeast US (Fig. 3). The ecosystem service values calculated with the NLCD are also area dependent; the western states have very small values per square meter when the total area of the state is considered (Fig. 3). However, the southern states show high ecosystem service values per square meter as well as high total ecosystem service values (Fig. 3).

New Mexico, which showed a -0.78% change, is the only state in the conterminous US that decreased in total ecosystem service value. Twelve of the fourteen states that less than doubled in total ecosystem service value are found west of the Mississippi River (West Virginia and Rhode Island are the exceptions) (Fig. 3). Twenty-one states showed increased ecosystem service values of 100–300%. Most of these states are in the interior and northeast US (Fig. 3). Ecosystem services for states in the Upper Great Lakes and across the southeastern US more than tripled in value (Fig. 3).

The total ecosystem service value calculated from each dataset was compared to the 1998 gross state product (GSP) for each state. GSP is the value added in production by the labor and property located in a state. GSP for a state is derived as the sum of the GSP originating in all industries in the state (Bureau of Economic Analysis, 2000). The GSP of any given state is highly correlated with the state's total population ($R^2 = 0.98$); however, the total value of the ecosystem services in a state are poorly correlated with GSP ($R^2 = 0.06$). The total GSP for the conterminous US was over $8.6 trillion in 1998, which is more than an order of magnitude greater than the total value of the spatially corresponding ecosystem service values measured at the fine resolution (Table 1). This contrasts dramatically with the global ecosystem service valuation ($33 trillion) ratio to global GDP ($18 trillion) originally calculated by Costanza et al. (1997). However, this is easily explained by the fact that the US represents a large fraction of the global GDP and contains much less than one-third of the world's ecosystem services. In addition, the US has a great deal of land dedicated to agriculture, which does not have a very high ecosystem service valuation.

Another means of evaluating the scale dependence of ecosystem service valuation was explored by simply aggregating the 30 m NLCD data to 10 coarser resolutions by a simple majority rule. This analysis was conducted for three states: Oregon, Colorado, and Delaware (Fig. 4). For all states total value dropped quickly with aggregation for pixels smaller than 1 km^2; however, this drop plateaued for coarser aggregations. A log–log analysis of ecosystem service value as a function of spatial resolution does produce strong linear relationships for each state; however, the slope values vary from state to state and appear to be a function of the initial endowment of high value small area land-covers such as wetlands, lakes, and rivers. The intercepts are driven by total value, which is primarily driven by areal extent of the region in question. It thus seems that the greater a proportion of ecosystem value contributed by wetlands, lakes, and rivers at the finer resolution is predictive of a greater percentage drop in total value as a result of aggregation to a coarser resolution (Fig. 4).

Despite the problems of scale dependence of ecosystem service valuation we took the liberty of calculating the ecosystem service value of each country of the world using the 1 km^2 resolution IGBP dataset. Table 2 summarizes the Land area, Population, Total national value of ecosystem services ('eco-value'), eco-value per capita, and eco-value per square kilometer (with ranks of the last three in adjacent columns). Not surprisingly the large countries of the world dominated the top 10 list for total eco-value: Russia, Canada, Brazil,

Table 1
Total ecosystem service value calculated for each state in the conterminous United States using the 1-km IGBP dataset and the 30-m NLCD dataset

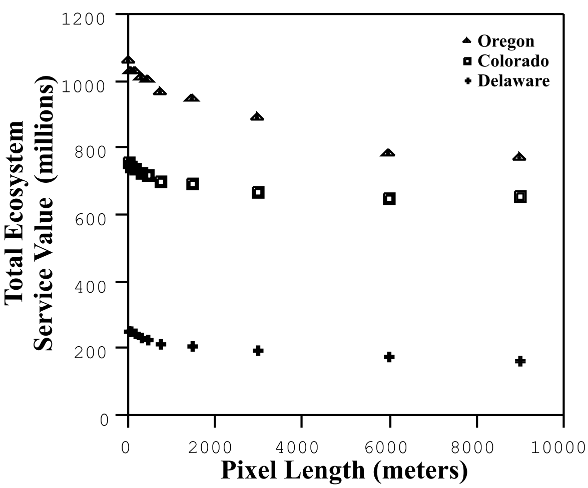
State	Total value ($/yr)		Percent change	Total GSP (1998)	IGBP Rank	NLCD Rank	GSP Rank
	IGBP	NLCD					
Alabama	4503687200	18346990583	307.38	109833000000	25	13	25
Arizona	8017483500	8675243391	8.20	133801000000	9	29	23
Arkansas	4069014600	20698062340	408.68	61628000000	29	12	34
California	12510613900	15947766717	27.47	1118945000000	3	15	1
Colorado	6908720600	7600381790	10.01	141791000000	14	34	22
Connecticut	502248900	2027508999	303.69	142099000000	46	46	21
Delaware	407976300	1498119758	267.21	33735000000	47	47	40
Florida	14469572300	75111734164	419.10	418851000000	2	1	5
Georgia	4983951300	30717442448	516.33	253769000000	21	6	10
Idaho	6672182900	9342913256	40.03	30936000000	15	26	42
Illinois	2693271800	9519627554	253.46	425679000000	36	25	4
Indiana	1593270700	4587109620	187.91	174433000000	42	39	15
Iowa	1940710400	6957517667	258.50	84628000000	38	36	29
Kansas	4219287500	7809268913	85.09	76991000000	27	32	31
Kentucky	3088902000	6716679028	117.45	107152000000	35	37	26
Louisiana	11698708200	55480908359	374.25	129251000000	4	3	24
Maine	7341015200	18294722895	149.21	32318000000	13	14	41
Maryland	1655856300	4569998718	175.99	164798000000	40	40	16
Massachusetts	1620676200	3967292037	144.79	239379000000	41	42	11
Michigan	6444293400	44287293616	587.23	294505000000	16	4	9
Minnesota	10225584900	74427364429	627.85	161392000000	6	2	18
Mississippi	3601168600	24230764239	572.86	62216000000	32	9	33
Missouri	4599752500	12622120593	174.41	162772000000	24	19	17
Montana	10367366500	14449635578	39.38	19861000000	5	16	45
Nebraska	3301666200	12366335013	274.55	51737000000	34	20	36
Nevada	7432786600	9217854415	24.02	63044000000	11	27	32
New Hampshire	1352946000	2888247710	113.48	41313000000	43	43	38
New Jersey	1106637300	4359918990	293.98	319201000000	45	41	8
New Mexico	8603630100	8536204881	−0.78	47736000000	8	31	37
New York	6114041300	24063754072	293.58	706886000000	19	10	2
North Carolina	4938818400	28836411607	483.87	235752000000	22	7	12
North Dakota	3787340000	13578059765	258.51	17214000000	30	17	47
Ohio	2144419000	4959008015	131.25	341070000000	37	38	7
Oklahoma	6373808300	8787901657	37.88	81655000000	17	28	30
Oregon	7906203900	11616972178	46.93	104771000000	10	23	27
Pennsylvania	3346573800	6990823234	108.89	364039000000	33	35	6
Rhode Island	278187200	551661188	98.31	30443000000	48	48	43
South Carolina	4407312900	21381967855	385.15	100350000000	26	11	28
South Dakota	5067680200	12302455227	142.76	21224000000	20	21	44
Tennessee	3707065800	8591500537	131.76	159575000000	31	30	19
Texas	19884822600	42540619971	113.94	645596000000	1	5	3
Utah	9283508500	12181960137	31.22	59624000000	7	22	35
Vermont	1331784100	2744309188	106.06	16257000000	44	44	48
Virginia	4075739900	10008878086	145.57	230825000000	28	24	13
Washington	6128654600	7611500850	24.20	192864000000	18	33	14
West Virginia	1830552800	2400885977	31.16	39938000000	39	45	39
Wisconsin	4804205300	26117804983	443.64	157761000000	23	8	20
Wyoming	7427162900	12659957576	70.45	17530000000	12	18	46
	258770863400	773181459803	198.79	8627168000000			

Ecosystem service values are also compared to the total GSP for each state. GSP data provided by Bureau of Economic Analysis, US Department of Commerce (Bureau of Economic Analysis, Regional Accounts Data, GSP Data Website 2000).

United States, Zaire, China, Australia, Indonesia, Peru, and Columbia. Somewhat surprisingly, many small island nations had high eco-values per capita despite the fact that this valuation did not include their very valuable marine resources. This effect caused large countries with small populations, such as Canada and Australia, to not rank as highly in eco-value per capita as we expected (Canada 109, Australia 114 out of 216). Hong Kong ranked last in eco-value per capita. Small island nations and protectorates also dominated the eco-value per square kilometer category also. It is not clear how these values would change if measured at a finer resolution. As this study of the influence of 'scale of measurement' on the ecosystem service value of the 48 conterminous states has shown, there is no simple mathematical relationship between scale of measurement and ecosystem service value.

4. Discussion

This investigation was fundamentally a simple empirical analysis of some of the scale and classification problems that can result when land-



State	% Change in Ecosystem Service Value 30 m to 9 km	% of Total Value in Wetlands and Water @ 30 m resolution
Colorado	13	17
Oregon	28	41
Delaware	36	98

Fig. 4. Ecosystem service value as a function of spatial resolution for three selected states.

cover is used as a proxy measure of ecosystem services. Land-cover types may be classified differently between datasets simply due to differences in spatial resolution. If a land-cover type does not cover most of a 1-km pixel, then it is essentially not recorded in the classified dataset. For example, if a pixel contains both wetlands and forest, it will be classified as Temperate Forest, if that is the dominant land-cover type. It is easy to surmise that the land-cover dataset created using 30-m Landsat TM imagery is more accurate than the biome dataset created using NOAA-AVHRR imagery; however, one must remember that the datasets serve very different purposes and any national or global studies would be virtually impossible to do using 30 m data (the state of Texas alone at 30 m is over 350 MB of information).

As suggested by Moody and Woodcock (1994) and Turner et al. (1989), the extent of fragmented ecosystems such as wetlands and Lakes/Rivers increased in the finer resolution NLCD dataset. This increase in rare ecosystems, which have very high ecosystem service values, contributed to the increased total ecosystem service value for each state (except New Mexico). States such as Nevada, Colorado, and Arizona, which have relatively large non-fragmented ecosystems, did not change much in total ecosystem service value. The total ecosystem service value for states in the western US did not greatly increase when using the NLCD dataset because the common land-cover types have similar ecosystem service values. For example, in Colorado, the extent of Temperate Forest ($302/ha/yr) and Grasslands ($232/ha/yr) increased, but the amount of Shrublands ($267/ha/yr) decreased. Thus, the total value of Colorado's ecosystem services increased by approximately 10%. The total ecosystem service value for New Mexico decreased because Ice/Rock, Urban, and Croplands, which have low ecosystem service values, increased in areal extent.

The value of ecosystem services increased for the US when the extents of ecosystems were classified from remotely sensed imagery with 30-m resolution. However, finer and finer spatial resolution does not imply greater and greater ecosystem service values. Classification accuracies decrease for forests when the spatial resolution becomes finer than 60–80 m (Woodcock and Strahler,

Table 2
Total ecosystem service value calculated for each nation of the world using 1 km^2 IGBP global land-cover dataset

Country	Land area	Population	Total ecosystem service value	Rank	Eco-value/capita	Rank	Eco-value/Land area	Rank
Russia	16780754	147264000	2129496072450	1	14460	116	126901	55
Canada	9723593	30142000	1105062854750	2	36662	109	113648	70
Brazil	8504610	160343000	999579034350	3	6234	128	117534	67
United States	9243498	267661000	442834652950	4	1654	161	47908	145
Zaire	2321494	47440000	349946993500	5	7377	125	150742	38
China	9334047	1236683000	337265130650	6	273	209	36133	167
Australia	7692332	18300000	287011617350	7	15684	114	37311	163
Indonesia	1897908	204323000	271332349100	8	1328	170	142964	42
Peru	1291670	24362000	161237112700	9	6618	126	124828	58
Colombia	1140754	37418000	155330889650	10	4151	138	136165	46
Venezuela	915292	22576000	121712564150	11	5391	132	132977	48
Mexico	1960807	95724000	110990219650	12	1159	172	56604	127
Bolivia	1087463	7810000	106627343450	13	13653	118	98051	81
Argentina	2780863	35558000	102159298900	14	2873	147	36737	164
India	3090083	969729000	101270489950	15	104	214	32773	171
Sudan	2490361	27899000	87545899950	16	3138	144	35154	168
Kazakstan	2661544	16433000	85857041400	17	5225	133	32258	174
Papua-New Guinea	462697	4405000	80601592250	18	18298	113	174200	28
Nigeria	907406	107129000	77631781100	19	725	183	85554	87
Angola	1252004	11569000	72425874750	20	6260	127	57848	123
Myanmar	668235	46822000	71857194250	21	1,535	165	107533	73
Congo	345286	2583000	56535469900	22	21888	111	163735	34
Cameroon	464254	13937000	55312376100	23	3,969	139	119142	65
Sweden	442723	8854000	50093925900	24	5,658	130	113150	71
Gabon	260638	1190000	49617646850	25	41696	106	190370	23
Madagascar	594648	14062000	49019036300	26	3,486	140	82434	96
Côte d'Ivoire	321681	14986000	48506574500	27	3,237	143	150791	37
Tanzania	895034	29461000	47668976100	28	1,618	162	53259	133
Mongolia	1559131	2426000	47373187500	29	19527	112	30384	178
Ethiopia	1128929	58733000	43724526400	30	744	181	38,731	159
Finland	332502	5144000	43165354100	31	8,391	122	129820	52
Chile	744403	14500000	42853019625	32	2,955	146	57567	125
Japan	373170	126054000	42680900350	33	339	202	114374	69
Turkey	777260	63674000	41492270900	34	652	184	53383	132
Malaysia	329329	21018000	41015057550	35	1951	157	124541	60
Zambia	752855	9350000	40014320550	36	4280	137	53150	134
South Africa	1222964	42465000	39731630700	37	936	175	32488	173
Guyana	211097	847000	37921074750	38	44771	105	179638	27
Iran	1624087	67540000	33739465850	39	500	194	20774	195
Norway	315215	4408000	33473248250	40	7594	124	106192	75
Mozambique	781415	18355000	32771166900	41	1785	160	41938	151
Ghana	240177	18102000	32692020600	42	1806	159	136116	47
Thailand	513563	60088000	31487162600	43	524	193	61311	117
Suriname	145592	437000	30991873650	44	70920	101	212868	20
Central African	621480	3342000	30675575250	45	9179	121	49359	142
Laos	230587	5117000	28900217150	46	5648	131	125333	57
New Zealand	266171	3628000	28389587500	47	7,825	123	106659	74
Kenya	580060	28803000	27644245050	48	960	174	47658	146
Ecuador	255776	11999000	26513087000	49	2,210	154	103657	77
Mali	1256712	9945000	26058597950	50	2,620	149	20736	196

Table 2 *(continued)*

Country	Land area	Population	Total ecosystem service value	Rank	Eco-value/capita	Rank	Eco-value/Land area	Rank
Guinea	246073	7495000	25224887250	51	3,366	141	102510	78
France	546511	58633000	24517460500	52	418	196	44862	149
Paraguay	400162	5093000	24215361200	53	4,755	136	60514	120
United Kingdom	242151	58800000	24066833300	54	409	198	99388	80
Spain	504708	39330000	23758115750	55	604	186	47073	148
Vietnam	325489	75123000	22992031250	56	306	205	70638	111
Philippines	291277	73419000	22315407050	57	304	206	76612	102
Greenland	2121203	57000	21976558100	58	385554	69	10360	209
Ukraine	595402	50719000	21688109550	59	428	195	36426	165
Nicaragua	128634	4351000	21544737900	60	4952	134	167489	31
Botswana	579971	1501000	21100721550	61	14058	117	36382	166
Chad	1154317	6984000	20006419400	62	2865	148	17332	201
Namibia	825723	1727000	18788164900	63	10879	120	22754	191
Vatican City	300072	57429000	18188733400	64	317	204	60615	118
Pakistan	877697	137752000	18045365150	65	131	213	20560	197
Uganda	213572	20605000	17999825850	66	874	178	84280	92
Algeria	2320833	30800000	17489389950	67	568	190	7536	211
Cambodia	182233	11164000	16980643100	68	1521	166	93181	84
Morocco	403820	28217000	16666451750	69	591	188	41272	152
Somalia	638852	10217000	16280233600	70	1593	163	25484	186
Bangladesh	137914	122219000	16246861900	71	133	212	117804	66
fr. Guyana	83879	159000	16206583550	72	101928	98	193214	22
Zimbabwe	390775	11423000	15214255000	73	1332	169	38934	158
Saudi Arabia	1950788	19494000	14547973100	74	746	180	7457	212
Germany	355387	82022000	14536689600	75	177	211	40904	153
Afghanistan	641897	25800000	14101092500	76	547	191	21968	193
Benin	116533	5946000	14057439950	77	2364	153	120631	64
Liberia	96335	2257000	13751350350	78	6093	129	142745	43
Iraq	435795	21177000	12730672550	79	601	187	29213	179
Honduras	112318	5751000	12605835250	80	2192	156	112233	72
Niger	1183054	9788000	12427394050	81	1270	171	10505	208
Senegal	197072	8762000	11831339600	82	1350	168	60036	121
Sierra Leone	72603	4428000	11254849300	83	2542	150	155019	35
Kyrgyzstan	199152	4606000	11104793100	84	2411	151	55760	129
Guatemala	109485	11241000	10942017750	85	973	173	99941	79
Turkmenistan	471136	4572000	10932961300	86	2391	152	23206	190
Poland	310689	38648000	10653897400	87	276	208	34291	169
Cuba	109335	11068000	9683132300	88	875	177	88564	86
Greece	131130	10522000	9443543550	89	898	176	72017	108
Uzbekistan	414v388	23672000	9312114900	90	393	200	22472	192
Korea, North	122017	24317000	9114759550	91	375	201	74701	106
Romania	236558	22535000	9074138100	92	403	199	38359	161
Panama	74119	2698000	9000156100	93	3336	142	121428	63
Burkina Faso	273681	10891000	8961771800	94	823	179	32745	172
Korea, South	96371	45850000	8154724600	95	178	210	84618	91
Togo	57242	4736000	7293394650	96	1540	164	127413	54
Mauritania	1041416	2392000	7076419100	97	2958	145	6795	214
Uruguay	178160	3223000	7075985250	98	2195	155	39717	156
Equatorial Guinea	27024	420000	6560746300	99	15621	115	242775	15
Yemen	420935	15214000	6282779850	100	413	197	14926	203
Costa Rica	51474	3466000	6262639850	101	1807	158	121666	62
Dominican Repub.	48372	8222000	6096740100	102	742	182	126039	56

Table 2 *(continued)*

Country	Land area	Population	Total ecosystem service value	Rank	Eco-value/capita	Rank	Eco-value/Land area	Rank
Malawi	96906	9609000	5870057000	103	611	185	60575	119
Egypt	982335	64792000	5532039950	104	85	215	5632	215
Belarus	206718	10270000	5529702500	105	538	192	26750	182
Sri Lanka	65189	18665000	5423427450	106	291	207	83195	94
Ireland	69212	3609000	5365193500	107	1487	167	77518	100
Syria	187951	14951000	4866193400	108	325	203	25891	185
Nepal	147297	22641000	4842141800	109	213866	82	32873	170
Solomon Islands	26144	396000	4766598100	110	12036864	8	182321	25
Portugal	91899	9934000	4707510000	111	473879	61	51225	138
Haiti	27029	6611000	4532317700	112	685572	44	167684	30
Tajikistan	142277	5988000	4498461250	113	751246	40	31618	175
Bahamas	10074	285000	4497302000	114	15780007	3	446427	5
Tunisia	155332	9326000	4480751100	115	480458	59	28846	180
Estonia	45440	1454000	4408362100	116	3031886	16	97015	83
Latvia	64299	2457000	4373042500	117	1779830	23	68011	113
Bulgaria	110825	8321000	4361433100	118	524148	56	39354	157
Azerbaijan	85712	7582000	4255010000	119	561199	54	49643	141
Guinea-Bissau	32758	1112000	4252775900	120	3824439	14	129824	51
Austria	83719	8077000	3951216350	121	489194	58	47196	147
Lithuania	64831	3702000	3739892950	122	1010236	34	57687	124
Hungary	92795	10166000	3575461050	123	351708	74	38531	160
Georgia	69961	5411000	3562199750	124	658326	48	50917	139
Denmark	41623	5286000	3449817750	125	652633	49	82882	95
Switzerland	41187	7122000	3353541100	126	470871	62	81422	99
Belize	21965	224000	3301606850	127	14739316	6	150312	39
Croatia	55675	4772000	3181052950	128	666608	46	57136	126
Rwanda	25225	7738000	3143225000	129	406206	65	124608	59
Libya	1620522	5648000	3121573550	130	552687	55	1926	216
Eritrea	124680	3590000	2711991150	131	755429	39	21752	194
Vanuatu	11891	176000	2598671000	132	14765176	5	218541	18
Bosnia-Herzegov	52099	3600000	2522394400	133	700665	42	48415	144
Armenia	29852	3790000	2447615300	134	645809	50	81992	98
Oman	312409	2265000	2418164450	135	1067622	31	7740	210
New Caledonia	18622	192000	2400875750	136	12504561	7	128927	53
Netherlands	33602	15598000	2332990050	137	149570	91	69430	112
Taiwan	36076	21535000	2088416350	138	96978	99	57889	122
Albania	28749	3500000	2046259100	139	585	189	71177	110
Czech Republic	77501	10314000	2045387400	140	198312	85	26392	184
Western Sahara	269697	228000	1936343900	141	8492736	9	7180	213
Burundi	25467	6052000	1901923050	142	314264	75	74682	107
Jordan	90105	4448000	1621350050	143	364512	73	17994	200
El Salvador	20676	5935000	1562245150	144	263226	79	75558	104
Gambia	10788	1169000	1526221550	145	1305579	29	141474	44
Slovakia	49600	5384000	1516857850	146	281734	78	30582	176
Macedonia	25535	2121000	1417319500	147	668232	45	55505	130
Bhutan	39927	842000	1214267900	148	1442123	25	30412	177
Israel	20813	5838000	1101515550	149	188680	86	52924	136
Jamaica	10992	2576000	977070700	150	379298	70	88889	85
Falkland Is.	11111	2000	948273100	151	#######	1	85345	88

Table 2 *(continued)*

Country	Land area	Population	Total ecosystem service value	Rank	Eco-value/capita	Rank	Eco-value/Land area	Rank
Slovenia	19406	1984000	944049100	152	475831	60	48647	143
United Arab Emirates	79810	2308000	918074050	153	397779	67	11503	205
Swaziland	17185	1032000	864366500	154	837564	38	50298	140
Trinidad and Togo	5111	1276000	842631350	155	660369	47	164866	33
Moldova	33547	4312000	798633900	156	185212	88	23806	189
Lesotho	30347	2008000	742362000	157	369702	72	24462	187
Fiji	18141	826000	725729200	158	878607	36	40005	154
Brunei	5736	298000	711997100	159	2389252	19	124128	61
Cyprus	9212	746000	697287800	160	934702	35	75693	103
Belgium	30477	10162000	563208950	161	55423	104	18480	199
Lebanon	10241	3859000	561578700	162	145524	93	54836	131
Qatar	11126	560000	418657850	163	747603	41	37629	162
Sao Tome and Pr	1044	148000	377957850	164	2553769	17	362029	8
Comoros	1656	590000	374112900	165	634090	51	225914	17
West Bank	5774	1664000	367464150	166	220832	81	63641	116
French Polynesia	2210	226000	339070200	167	1500311	24	153425	36
Faroes Is.	1267	45000	335050250	168	7445561	10	264444	13
Djibouti	21643	634000	318457750	169	502299	57	14714	204
Kuwait	16938	1809000	269638400	170	149054	92	15919	202
Hong Kong	1009	6900000	168961600	171	25	216	167455	32
Western Samoa	2801	183000	158062800	172	863731	37	56431	128
Federated State	531	112000	148621700	173	1326979	28	279890	12
Guadeloupe	1603	436000	135013350	174	309664	76	84225	93
N. Marianas	325	53000	122177950	175	2305244	20	375932	7
Guam	559	156000	108932450	176	698285	43	194870	21
Mayotte*	363	105000	106695250	177	1016145	33	293926	11
Seychelles	329	78000	106225000	178	1361859	27	322872	9
The isle of Man	573	76000	103881000	179	1366855	26	181293	26
Cape Verde	3819	390000	101126200	180	259298	80	26480	183
Tokelau	191	2000	91484200	181	45742100	2	478975	4
Netherlands Antilles	706	211000	82939100	182	393076	68	117477	68
Antigua and Barbados	434	66000	82197600	183	1245418	30	189395	24
Br. Virgin Is.	265	13000	81167400	184	6243646	12	306292	10
Martinique	1079	397000	70489100	185	177554	89	65328	114
Bahrain	583	620000	56823200	186	91650	100	97467	82
St. Vincent and	328	119000	47659550	187	400500	66	145304	41
Mauritius	1982	1145000	47588800	188	41562	107	24010	188
Dominica	723	83000	47178800	189	568419	53	65254	115
Malta	262	379000	44706600	190	117959	97	170636	29
St. Helena	296	7000	44189600	191	6312800	11	149289	40
Tonga	327	99000	43339800	192	437776	64	132538	49
Palau	327	17000	43318350	193	2548138	18	132472	50
Singapore	506	3462000	42915800	194	12396	119	84814	89
Saint Lucia	593	146000	42688500	195	292387	77	71987	109
Cayman Is.	174	36000	37738900	196	1048303	32	216890	19
Barbados	434	265000	36806100	197	138891	94	84807	90
Wallis & fut.	51	14000	31442600	198	2245900	21	616522	2
Gaza	374	1024000	30767600	199	30046	110	82266	97
Norfolk	35	2000	29743000	200	14871500	4	849800	1
Luxembourg	2596	422000	28341300	201	67159	102	10917	206

Table 2 *(continued)*

Country	Land area	Population	Total ecosystem service value	Rank	Eco-value/capita	Rank	Eco-value/Land area	Rank
Reunion	2549	692000	27193600	202	39297	108	10668	207
Am.Samoa	90	61000	22944600	203	376141	71	254940	14
st. p & m	93	7000	21451400	204	3064486	15	230660	16
St. Kitts-Nevis	136	42000	18559600	205	441895	63	136468	45
Grenada	303	96000	15548100	206	161959	90	51314	137
Anguilla	35	7000	13422250	207	1917464	22	383493	6
Aruba	164	67000	12608300	208	188184	87	76880	101
Niue	230	2000	10197600	209	5098800	13	44337	150
Andorra	457	68000	8972350	210	131946	96	19633	198
Montserrat	102	13000	7680000	211	590769	52	75294	105
Liechtenstein	164	31000	6556000	212	211484	83	39976	155
Monaco	8	32000	4436050	213	138627	95	554506	3
Nauru	22	11000	2287450	214	207950	84	103975	76
Pitcairn Is.	32	12	1699600	215	4907	135	53113	135
San Marino	59	25000	1650650	216	66026	103	27977	181

Table is sorted in descending order by total national ecosystem service value with Land area, Population, Eco-value per capita, and Eco-value per km^2 and their ranks as additional columns.

1987). Fine resolution data, such as the 10 m SPOT imagery, would produce results for individual trees rather than forest classes. Further analysis using finer resolution imagery is needed to determine if smaller pixel size does influence ecosystem service value.

The overall value of the US is actually higher than estimated here because the Great Lakes were excluded from this analysis. Coastal marine waters, which are valuable ecosystems, were also excluded from the analysis. Additionally, ecotones have high ecosystem service values although they are not specifically identified in either dataset. These areas are often classified differently in the two datasets. For example, many locations in the western US are classified as Shrublands in the IGBP dataset, but are classified as Grasslands in the NLCD dataset. These locations may be ecotones, and if so, should receive a different ecosystem service value.

Using land-cover as a proxy for ecosystem services presents both challenges and opportunities. The global coverage and increasing spatial, spectral, and temporal resolution of satellite imagery is a very practical means of making global land-cover measurements. The utility of these kinds of measures warrants further investigation with respect to assessing and monitoring both ecosystem services and the values derived from them. The spatially explicit nature of classified satellite imagery allows for the use of spatial context both within the image and relative to other geo-referenced data for improving both: (1) measurements of ecosystem functions, goods, and services; and (2) appropriately valuing those ecosystem functions, goods, and services.

The following two examples demonstrate how spatially referenced land-cover data can enhance measurements of both ecosystem functions, goods, and services and their valuation. (1) Vegetation provides erosion control services. The erosion control services of vegetation near a municipal reservoir protect the water storage capacity of that reservoir. Spatial context is essential for identifying the interaction/dependency between these services. (2) Transpiring trees contribute to the hydrologic cycle. Transpiring trees in a suburban environment can significantly reduce the costs of air conditioning in those neighborhoods. This particular ecosystem service can only be accounted for in urban areas that are hot and affluent enough to use air conditioning. This ecosystem service cannot be identified without multiple spatially referenced datasets.

The GUMBO model described in this issue is probably the first attempt to understand the dynamics of ecosystem services by coupling the dynamics of the physical earth to anthropogenic behavior (Boumans et al., 2002). Incorporating spatially explicit information about ecosystem services and their values into GUMBO or its progeny is an interesting future challenge. The spatial distribution of the benefits of ecosystem services provided by a particular place can range from the local to the global. How these ecosystem services are valued will also vary spatially. Comprehensive dynamic models such as GUMBO might be greatly improved by incorporating spatially explicit information; however, spatial context issues present many problems to be solved even when trying to make only static assessments of ecosystem services and their economic value. This research only hints at how complex the seemingly simple issue of spatial scale of measurement can be.

5. Conclusions

When land cover is used as a proxy for ecosystem service the spatial scale at which the land cover is measured significantly influences measurements of both the ecosystem service extent and its valuation. In this comparison of two conterminous US datasets there was an increase in the areal extent of Lakes/Rivers, Urban, Ice/Rock, and Wetlands at the finer spatial resolution (the 30-m NLCD dataset). The change in extent of these land-cover types was consequently a significant factor in the amount of change in total ecosystem service value for each state. All states except New Mexico showed an increase in the total ecosystem service value when the value was determined using the finer resolution NLCD dataset. However, the relative changes in total ecosystem value for each state were quite variable. This indicates that the relative valuations of ecosystem services will not remain constant as spatial scale of measurement changes. For example, assume that the total value of Africa's ecosystem services was three times greater than the total value of North America's ecosystem services when measured at 1 km^2 resolution; this ratio is very unlikely to hold when the valuation is made at another scale. Overall, total ecosystem service value for the US increased from \$258 billion (1 km^2 IGBP data) to \$773 billion (30 m NLCD data) (a 198% increase).

The spatial variability of ecosystem services and their respective valuation presents many interesting problems. The 'scale of measurement' problem described here suggests that measurements of ecosystem services provided by high value and low areal extent biomes such as wetlands, rivers, and lakes must be evaluated very carefully. Despite these challenges, spatially explicit land-cover data used in conjunction with other geo-referenced political, economic, and physical data has the potential to greatly improve comprehensive dynamic models like GUMBO and enable more meaningful, accurate, and practical measurements of ecosystem services and their economic value.

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