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A Composite Index-Based Approach for Mapping Ecosystem Service Production Hotspots and Coldspots for Priority Setting in Integrated Watershed Management Programs

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Abstract

Despite the potential synergism, integrated watershed management and ecosystem services frameworks are rarely used jointly to address the myriad of current water-related issues. The two frameworks are used in this study to spatially identify ecosystem hotspots and coldspots for priority setting in natural resource management programs. Inferred proxies of carbon storage, groundwater supply, surface water supply, and soil retention ecosystem service production potentials were quantified for Texas, U.S., using two complimentary hydro-ecological models, and valued using a non-monetary multi-criteria valuation approach. Maps of individual and composite ecosystem service values showed that several services were co-located and unevenly distributed with most of the high-value hotspots clustered in the eastern part of the state. Individual impacts of land use, climatic and soil properties on the distribution and value of ecosystem services across space were discernable. The study underscored the need for holistic management of landscapes to take advantage of the multiplicity of benefits provided by nature. The approach can readily be incorporated into resource management programs to identify high-value ecosystem service production areas that need conservation, low-value areas that may need restoration, and anthropogenic activities influencing the distribution of ecosystem services.

Keywords

HAWQS, InVEST, Multi-Criteria Analysis, Spatial Analysis, Sustainability

1. Introduction

Landscapes provide a variety of water and climate regulation functions that are vital to humanity. They regulate water flow through canopy interception, litter absorption, storage in soils and under the ground. This, in turn, determines the timing and magnitude of runoff, flooding, and groundwater recharge. With runoff as the main driver of water-induced erosion, landscapes provide an important function of minimizing rates of soil loss by regulating water flow. Landscapes also regulate climate by, among others, sequestrating carbon from the atmosphere and storing it underground (Lal, 2008), thereby decreasing greenhouse gases in the atmosphere.

The delivery of these water-related ecosystem services (WrES) is influenced by the landscape's landcover-soil-terrain characteristics (With, 2019). Because of the landscape's spatial heterogeneity, these services, vary across space. WrES are also intangible, do not have market values, and are difficult to quantify and value economically (Coates et al., 2013). In many cases, people are not even aware that the surrounding landscape provides these services and so, do not put emphasis on conservation and protection of the landscape. Moreover, the supply of these services is also threatened by unsustainable anthropogenic activities (Reid et al., 2005). Quantification, valuation, and mapping of these services can show high-value ecosystem service (ES) production areas (hotspots) that need to be protected or low-value areas (coldspots) that may need to be restored to ensure adequate ES levels. Threats to ES can also be identified by comparing the spatial distribution of ES to maps of activities that affect the landscape's ability to provide ES. Assessments can also highlight the multi-functionality of landscapes (Grizzetti et al., 2016), justifying the need for investments in integrated watershed management (IWM).

The incorporation of the concept of ES into policymaking has been derailed due to several factors. At local scales, ES assessments have traditionally relied on site-specific quantification of benefits accrued from the landscape, despite this being a tedious and expensive process (Schägner et al., 2013). These small-scale assessments are hard to scale up to levels relevant to the management of ES (Birkhofer et al., 2015). On the other end of the spectrum, ES valuations at large scales are often based on extrapolated data from site-specific values (Liekens & De Nocker, 2013). Scaling up does not accurately represent the heterogeneity of complex landscapes and can lead to over or underestimation of ES. Even when quantified, the process of valuing and compounding benefits provided by landscapes is challenging. Different ES are quantified in different units and thus cannot be compared or aggregated.

Several studies recommend the use of hydro-ecological modeling approaches for the quantification of ES (Vigerstol & Aukema, 2011; Volk, 2013). They argue that at both large and small spatial scales, ES assessments can benefit from landscape-scale process-based modeling approaches, mostly applied in simulating hydrological processes in IWM analyses. IWM programs also stand to benefit from the incorporation of WrES concepts. IWM programs require the determination of baseline conditions, identification of critical areas, and development of criteria to measure the impact of proposed measures. One of the key bottlenecks of implementing watershed management plans has been the lack of established criteria to measure benefits accrued from management measures—a case that has led to less interest from private entities to invest in watershed protection measures (Kikoyo et al., 2020). Integration of ES valuation addresses this bottleneck.

Monetary approaches that assign dollar values to ES are widely used in the economic valuation of ES (Alam et al., 2016; Francesconi et al., 2016). However, these approaches are associated with high uncertainties due to the non-market nature of ES, the influence of societal perceptions of the monetary value of ES, and because quantification and valuation studies are often carried out separately (Schmidt et al., 2016). The uncertainty and complexity associated with monetary valuation approaches render the use of non-monetary valuation techniques worthy of consideration. Non-monetary techniques do not express the value of ES in dollar amounts and do not reflect preferences defined under budget constraints. Valuation may be as simple as expressing the state of ES in qualitative terms (e.g., "poor", "good", "excellent"). For cases where the value of ESs needs to be aggregated, qualitative descriptions or quantities of respective ES can be normalized into a single unit norm using mathematical concepts that are popular within the field of Multi-Criteria Analysis (MCA) (Langemeyer et al., 2016). Normalized quantities can then easily be aggregated and mapped to show ES production areas associated with e.g., high ES value.

This paper describes the development of a Composite ES Index (CESI), proposed for priority setting in watershed management programs. The composite index is derived by aggregating weighted normalized values of inferred carbon storage, groundwater supply, surface water supply, and soil retention potentials in a heterogeneous landscape. Two hydro-ecological models, the Hydrologic and Water Quality System (HAWQS) (Yen et al., 2016) and the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) (Sharp et al., 2018), were used to predict proxies of ES in Texas, U.S. Spatially explicit ES indices for the different ES proxies were determined using a multi-criteria based non-monetary valuation approach. Index values of individual services and the aggregated service were spatially mapped in their areas of production to highlight the distribution of these services and to show how they vary with land use, climate, and landscape physiography.

2. Methods

2.1. Study Area

The study identified ES production hotspots and coldspots based on an MCA-derived composite ES index from imputed spatial maps of potential carbon storage, soil retention, aquifer recharge, and surface water supply indices for 1081 sub-watersheds in Texas, U.S. The huge expanse of Texas encompasses several regions with distinctly different climates, soils, land cover, and terrain (**Figure 1**).

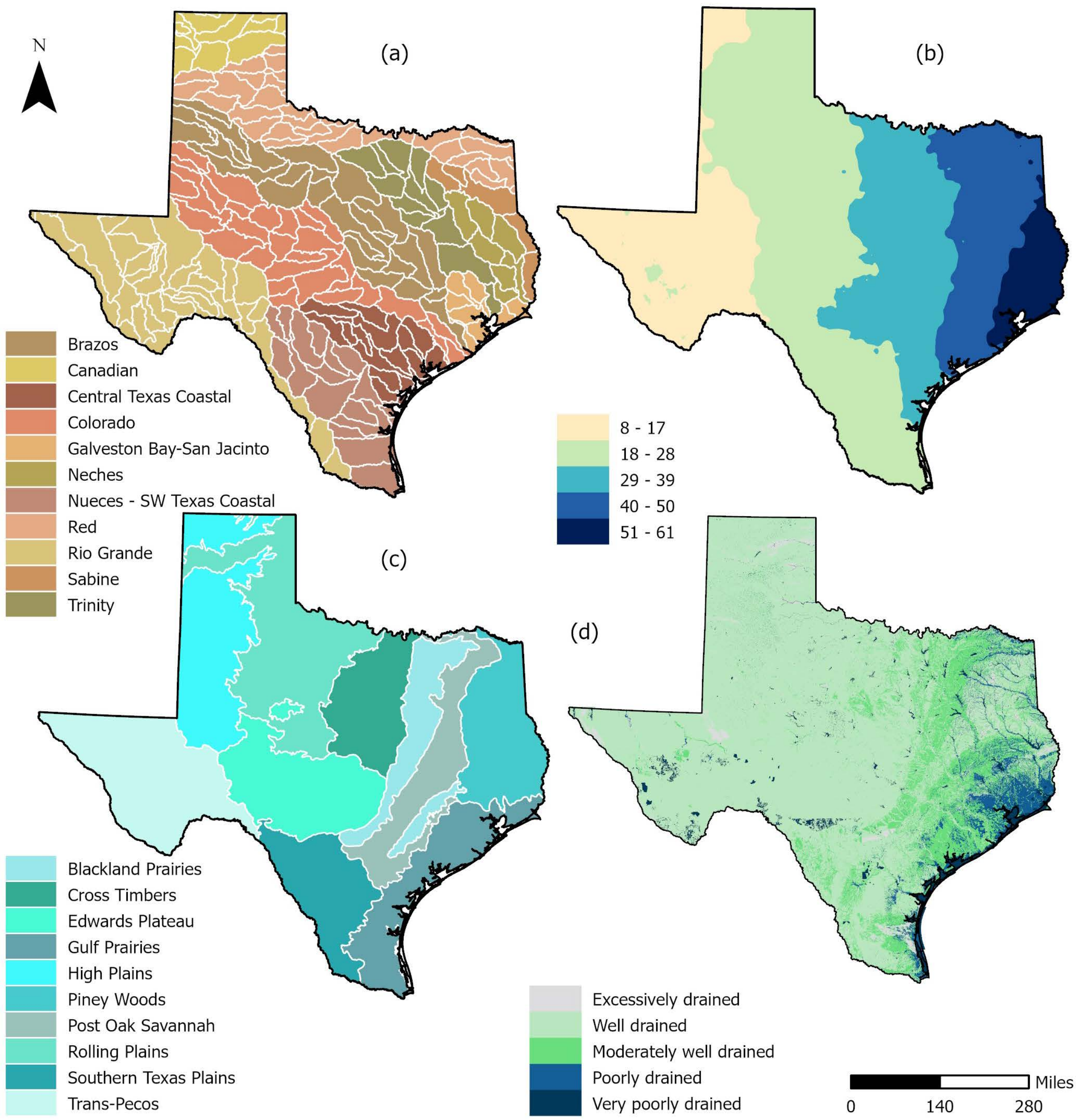

Figure 1. (a) Major river basins in Texas; (b) Isohyet map of Texas illustrating decreasing precipitation averages, East to West; (c) Ecological regions; (d) Soil drainage characteristics.

The diversity of the physiographic features of the State makes it an ideal candidate for evaluating how those features influence the locale, quantity, and distribution of ES.

Texas is the largest contributor to greenhouse gas emissions in the U.S. (Han et al., 2007), groundwater supplies that account for about 60 percent of the State's water needs are declining (Wurbs, 2015), and sedimentation is notably responsible for the reduction of reservoir storage capacity across the state. It is vital that areas in the State that replenish water resources, and those with carbon storage potential be identified and protected.

2.2. Estimation of Water Percolation, Surface Runoff, and Soil Loss Using HAWQS

HAWQS is a web-based water quantity and quality modeling framework that uses the Soil and Water Assessment Tool (SWAT) (Srinivasan et al., 1998) as its modeling platform. As a hydrologic model, SWAT has been widely used to simulate watershed processes at different spatial scales (Francesconi et al., 2016). SWAT's watershed initialization and characterization processes require a lot of time and computing resources, especially when simulating large geographical areas. HAWQS advances the functionality and ease of application of SWAT by minimizing the necessary initialization time. Setup and modeling of hydrological processes using the HAWQs model is detailed in Yen et al. (2016).

A calibrated HAWQS model was used to simulate hydrological processes for all 1081 sub-watersheds for the entire state of Texas at an annual timescale. Annual estimates were appropriate since the long-term ecosystem condition of the watersheds was being studied. The simulation period covered 30 years (1986-2015) after a 3-year warm-up period (1983-1985). During watershed definition, the threshold for hydrologic unit discretization was set at zero so that the contribution of all land use categories, soil, and slope properties were considered.

2.3. Carbon Storage Estimation Using the InVEST Model

The InVEST's Carbon Sequestration and Storage (CCS) module is used to estimate the total carbon stored in terrestrial landscapes by aggregating carbon stored in both aboveground and belowground live biomass, dead aboveground litter, and in the soil. The module requires the input of a classified land cover/land use raster and estimates of carbon stored in each carbon pool for a particular land use category. The methodology for estimating carbon storage using the InVEST model is detailed in Sharp et al. (2018).

Soil carbon pool estimates (**Table 1**) for Texas were processed from the 2019 gridded nationwide Soil Survey Geographic Database (gSSURGO) database (NRCS, 2020) which contains weighted average soil organic carbon (g·C/m^2) values. Above and below ground carbon pool estimates used for forested areas were obtained

Table 1. Land use and average carbon pool estimates used for modeling carbon storage in Texas.

Land Use	Carbon Pool Estimates (Mg C/ha)			
	C above	C below	C soil	C dead
Water	0	0	0	0
Built-up area	5	3	20	0
Forest land	90	60	110	30
Rangeland	6	6	20	2
Cropland	3	2	8	1
Wetland	10	5	25	0

from the national carbon density stock estimates (Woudenberg et al., 2010). Estimates of carbon stored in either pool for the remainder of the land-use categories were sourced from Sharp et al. (2018), Qiu and Turner (2013), and Smith et al. (1997).

2.4. Valuation of Ecosystem Services Using a Multi-Criteria Analysis Approach.

Using MCA, long-term (30 years) mean annual percolation (mm), runoff (mm), soil loss (kg), and carbon storage density (Mg C) for all sub-watersheds in Texas were normalized using a maximization function, while a minimization function was applied for soil loss. This was because the objective of natural resource management programs is to minimize soil erosion rates, maximize percolation for groundwater recharge, augment water yield for reservoir recharge, and enhance carbon storage. The relative importance of each ES proxy was considered by assigning weights that highlight the benefit of a service being produced in one area vis a vis another area. This is important because, for instance, a downstream watershed with high runoff rates but which drains directly into the ocean may not benefit more people than an upstream watershed with similar or low runoff rates. To map the ES hotspots and coldspots, individual and aggregated ES normalized values were classified into quintiles. Sub-watersheds with values in the upper quintile were categorized as hotspots. Coldspots were those in the lowest quintile.

The weighting criteria considered 1) whether a watershed was under-lain by a minor, major, or no aquifer in assigning weights to watersheds for the groundwater recharge (GWR) ES, 2) the number of reservoirs downstream of a watershed for the surface water supply (SWS) ES, 3) soil productivity of a watershed for the soil retention ES, and 4) the quantity of Carbon emitted from the watershed for the Carbon storage ES. The soil productivity map for Texas was processed from the soil productivity index dataset for the entire conterminous U.S. (Schaetzl et al., 2012). Carbon emissions data was obtained from the USEPA greenhouse Gas inventory database. For all criteria, the weighting was based on a 3-point Likert scale (**Table 2**). To map the ES hotspots and coldspots, ES values for individual services were aggregated and classified into five percentile groups (quintiles). Watersheds with values in the upper quintile (above the 80^{th} percentile rank) were categorized as hotspots. Coldspots were those in the lowest quintile.

3. Results

3.1. Provision and Spatial Distribution of ES

Potential groundwater recharge ES values were markedly high for areas in the east of the State. Downstream watersheds in the Sabine, Neches, and Red River basins in East Texas had the highest ES values. Specifically, the 1) Jim Bayou-Frazer Creek in the Red-Sulphur Basin, 2) Little Cow Creek in the Sabine Basin,

Table 2. Criteria for assigning weights to reflect the relative importance of ecosystem services across space.

Service	Weighting criteria	Likert scores/Multipliers (w = 1, 2, 3)	
Groundwater recharge (G)	Does an underlying aquifer exist to store the water that percolates?	$G_{nw} = \begin{bmatrix} G_n \times 3, & \text{for major aquifer} \\ G_n \times 2, & \text{for minor aquifer} \\ G_n \times 1, & \text{for no aquifer} \end{bmatrix}^{1,2}$	(1)
Surface water supply (R)	How many reservoirs (r) are located below the watershed?	$R_{nw} = \begin{bmatrix} R_n \times 3, & r > 5 \\ R_n \times 2, & 5 \geq r > 1 \\ R_n \times 1, & r \leq 1 \end{bmatrix}$	(2)
Soil retention (S)	The productivity of the soils within the watershed	$S_{nw} = \begin{bmatrix} S_n \times 3, & \text{for highly productive soils} \\ S_n \times 2, & \text{for moderately productive soils} \\ S_n \times 1, & \text{for low productive soils} \end{bmatrix}$	(3)
Carbon storage (C)	How much carbon (t/ha CO_2) is emitted (e) from the watershed?	$C_{nw} = \begin{bmatrix} C_n \times 3, & e \geq 100000 \\ C_n \times 2, & 100000 > e > 0 \\ C_n \times 1, & e = 0 \end{bmatrix}$	(4)

[1]G_{nw} is the normalized and weighted potential groundwater recharge index. [2]G_n is the normalized potential ground water recharge value. Similary, R_{nw}, S_{nw}, and C_{nw} are potential surface water supply, soil retention, and carbon storage indices respectively.

and 3) Turkey Creek-Village Creek in the Neches Basin provided the highest GWR-ES. These areas are underlain by the Gulf Coast and Carrizo-Wilcox major aquifers. Indices gradually decrease westwards (**Figure 2(a)**) and were lowest in the City of Socorro Watershed in the Rio-Grande Basin, in the headwaters of Blackwater Draw Watershed of the Brazos Basin, and the North Big Blue Creek Watershed of the Canadian River Basin.

Like potential GWR, values of the carbon storage ES were highest in the humid subtropics of the eastern part of the State covered with piney woods and lowest in the arid west and in the high plains of northern Texas (**Figure 2(b)**). Carbon storage potential was highest in West Fork San Jacinto River (San Jacinto), Big Sandy Creek (Neches), Little Cypress Creek (Sabine), Long King Creek (Trinity) watersheds and lowest in the Miller Airfield-Elephant Lake and East Rita Blanca Creek watersheds in the Canadian, and Frio Draw in the Red River basin. Substantial high-value carbon storage hotspots were scattered across the central part of the state, particularly in the Edwards Plateau region and in coastal areas. In these regions, most of the carbon storage potential was in the below-ground pool whereas high above ground carbon storage densities were concentrated in the northeastern part of the state.

The production of the Surface Water Supply (SWS) service was highest in the coastal watersheds of the Galveston-San Jacinto Bay area, in the downstream watersheds of Trinity and Neches Basins, and several watersheds located in the Middle Brazos and Upper Trinity Basins (**Figure 1(a)**, **Figure 2(c)**). In the Galveston-San Jacinto Bay area, indices were highest in the Brays Bayou and White

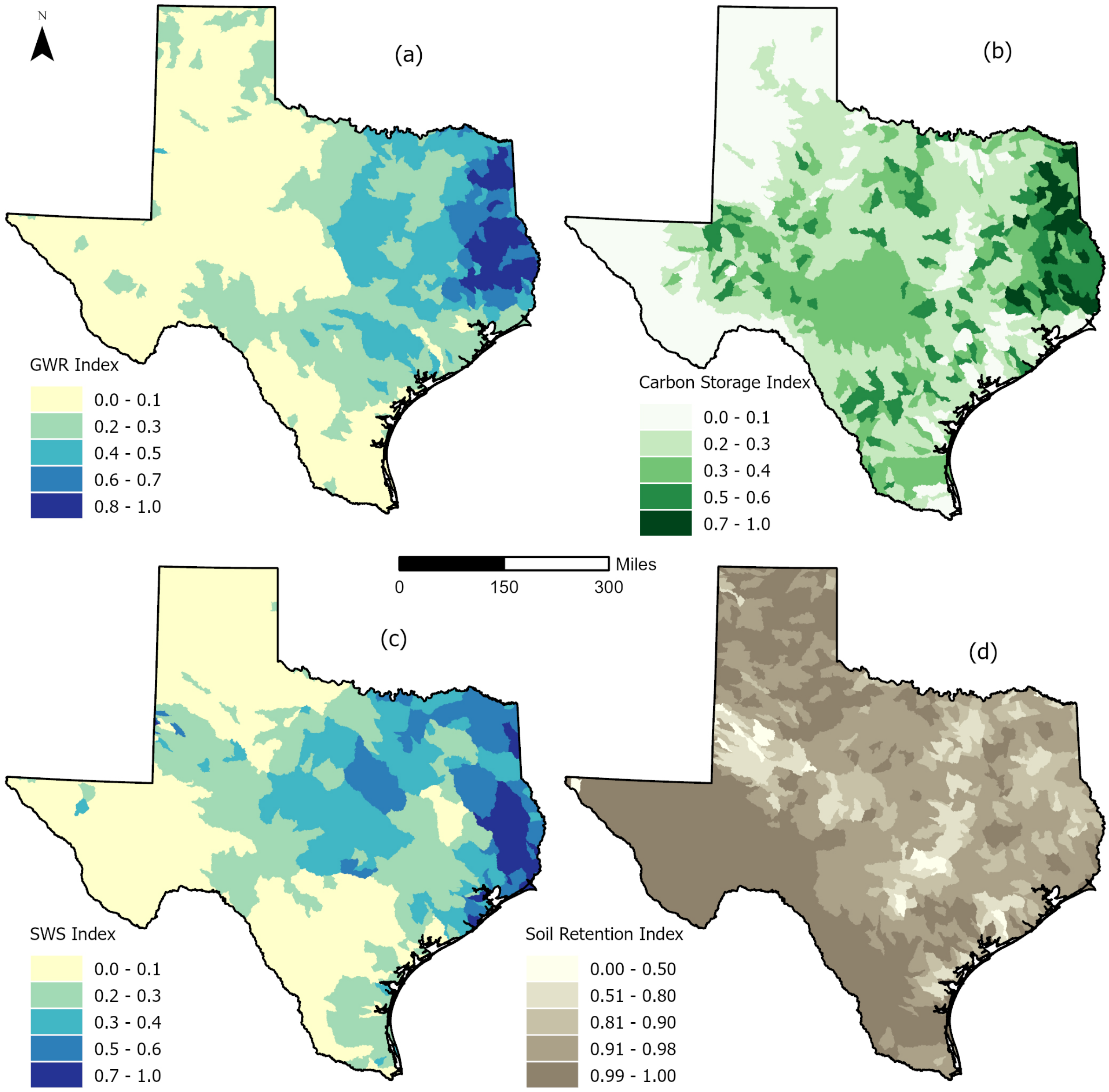

Figure 2. Modeled spatial distribution of index values of (a) groundwater recharge (GWR), (b) carbon storage, (c) surface water supply (SWS), and (d) soil retention ecosystem services in Texas.

Oak Bayou-Buffalo Bayou watersheds which are part of the urban greater Houston metropolitan area. Relatedly, in the upper Trinity Basin areas, surface water supply indices were highest in the Timber Creek and Big Fossil Creek watersheds which drain the Dallas-Fort Worth urban areas. Like groundwater recharge, indices were low both in the western and northern arid lands majorly due to low rainfall received in these areas. In both Upper Brazos and Trinity Basins, indices were also noticeably high in watersheds draining the Black Prairie ecoregion—typified by a high percentage of land under the cropland land-use system.

Soil erosion rates were generally high in the Blacklands Prairie ecoregion and in several parts of the coastal gulf prairies, all of which have relatively high percentages of land under the cropland system. Consequently, the soil retention ES was low in these highly agricultural watersheds (Figure 2(d)). Water-induced soil erosion was expectedly low in the Trans Pecos ecoregion receiving less than 500 mm of rainfall annually (Figure 1(c)).

Correlations between values of simulated ES were unexpectedly low (Figure 3). Of all the paired ES, SWS and GWR services had the highest correlation (0.49). The two ES are largely influenced by the amount of rainfall received. Similarly, GWR and carbon storage ES were fairly correlated, possibly due to the effect of biomass cover on the infiltration process. Correlations between values of simulated ES were unexpectedly low (Figure 3). Of all the paired ES, SWS and GWR services had the highest correlation (0.34). The two ES are largely influenced by the amount of rainfall received. Similarly, GWR and carbon storage ES were fairly correlated, possibly due to the effect of biomass cover on the infiltration process. The soil retention ES index had a negative correlation with other services.

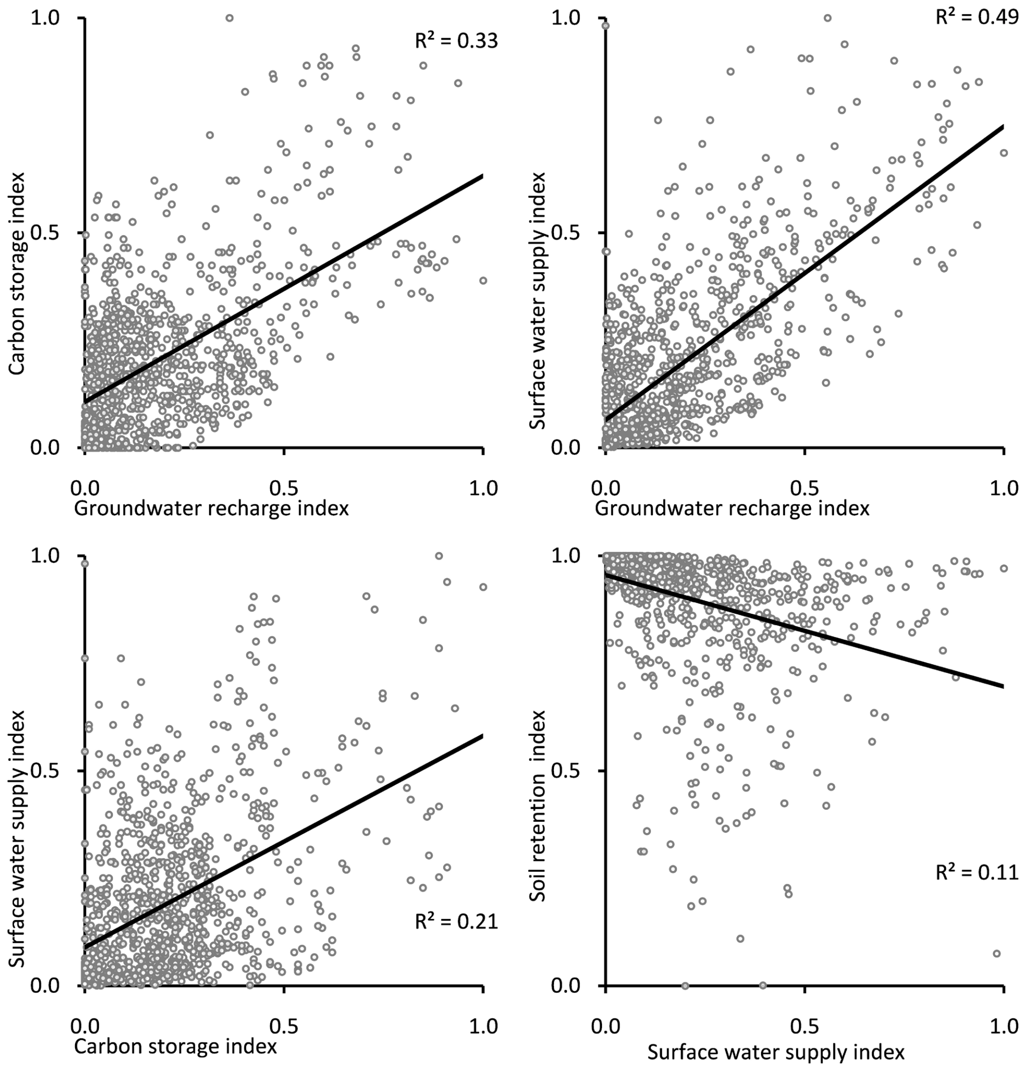

Figure 3. Pairwise correlation analysis of values of simulated ecosystem services.

3.2. Spatial Distribution of Coldspots and Hotspots Based on the Total Ecosystem Service Value

Figure 4 shows the values of total ES values categorized into quintiles. The first quintile with ES values below 1.2 shows the direst coldspots. Conversely, those in the fifth quintile, with ES values greater than 2.4 are the State's most healthy hotspots. In totality, most of the watersheds in Texas were coldspots (50%) with about 29% (310 watersheds) of the total watersheds in a dire state. Healthy ecosystems providing multiple ecosystem services were limited in Texas, accounting for only 12% (ES value > 18) of the total watersheds. The low percentage (6%) of watersheds with ES values > 2.4 out of a potential maximum of 4 highlights the scarcity of hotspots in Texas.

Most of the State's total ES hotspots were located in the east, with several patches of hotspots scattered in the central part of the State (Figure 4(a)). All four ES were considerably high in the humid areas of East Texas. Therefore, it comes as no surprise that most of the hotspots were located in this region. The Tenmile Creek and Big Sandy Creek watersheds in the Neches, the Old River watershed in the Trinity, and the Adams Bayou in the Sabine watersheds had the highest ES values.

4. Discussion

4.1. Factors Influencing the Location and Values of Ecosystem Services

High-value ES provision areas for groundwater recharge, surface water supply,

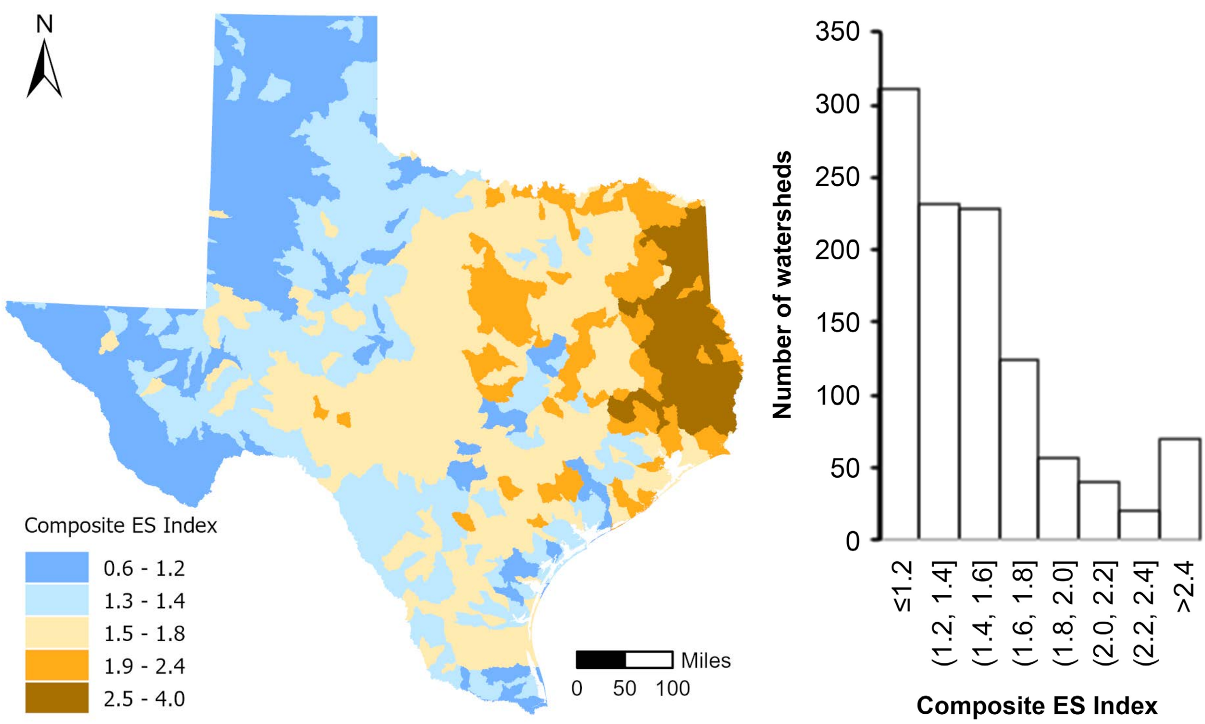

Figure 4. Spatial and frequency distributions of total ecosystem service values across Texas.

and carbon storage were co-located in the eastern part of the State and low values in the west, in congruent with the distribution of rainfall in the state. Conversely, soil retention values were higher in areas that received low amounts of rainfall. This is so, because, with minimal or no rainfall, rainfall-runoff induced soil loss is also minimal. This, however, does not mean that other types of soil erosion do not exist. Wind is the primary agent of erosion in this region. Pairwise correlations of rainfall and ES values were particularly high for rainfall with groundwater recharge and surface water supply ES values compared to correlations of precipitation with the rest of the ES (**Figure 5**).

Unlike the supply of the groundwater recharge ES that gradually decreased westwards congruently with decreasing precipitation, pockets of high- and low-value carbon storage, surface water supply, and soil retention ES were clustered across the state. The influence of land use on the location of surface water supply

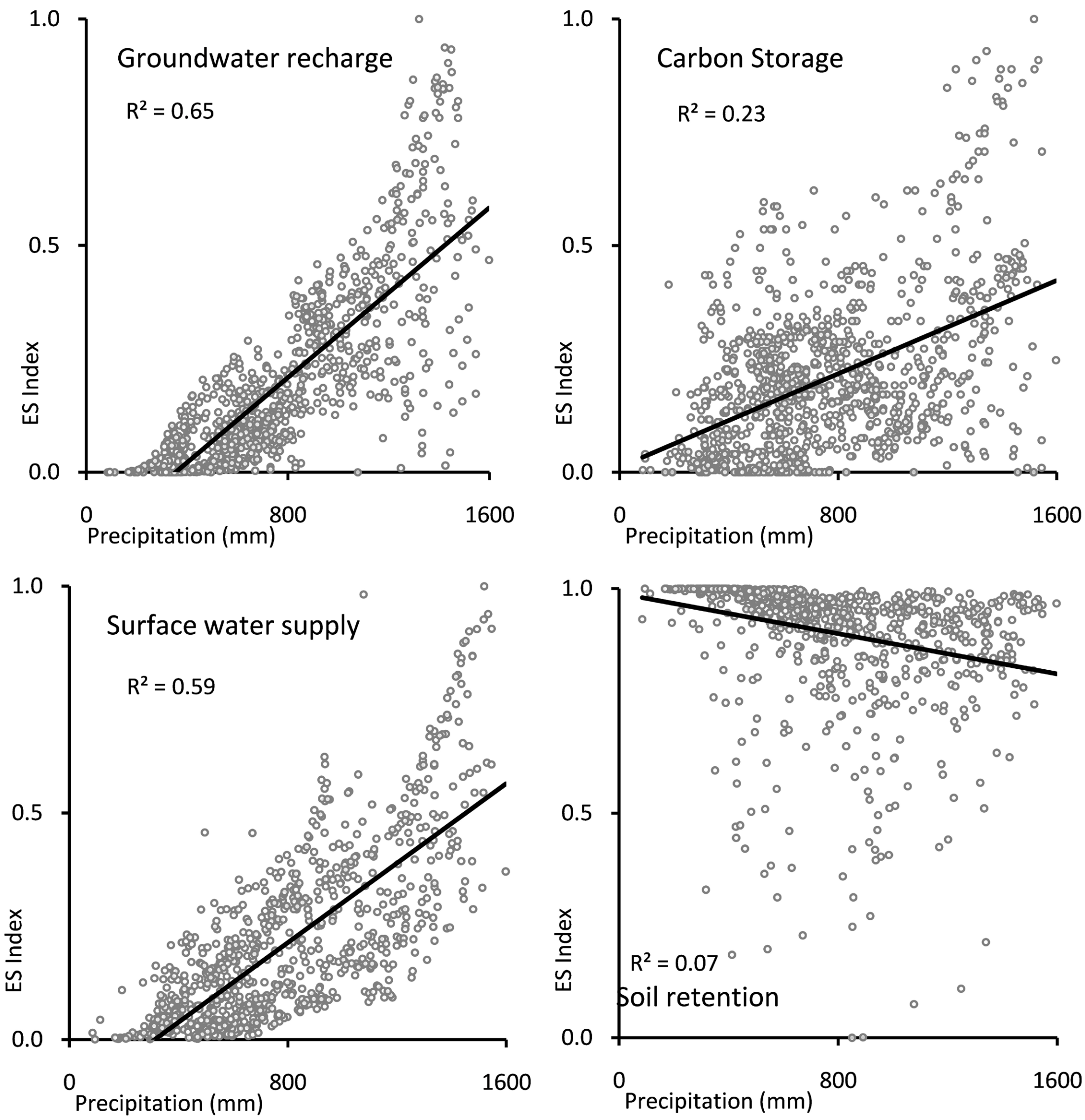

Figure 5. Relationship between precipitation and simulated ecosystem service values.

and soil retention services was discernible. Low-value soil retention production areas were in highly agricultural areas, whereas both urbanized and highly agricultural areas consistently had high surface water supply indices. The high scatter of the carbon storage ES was swayed by the high below-ground carbon storage potential. This pool had more carbon than the above ground phytomass. This is in agreement with global estimates that show that carbon stored in soils far exceeds the amount of carbon stored in phytomass and the atmosphere (Scharlemann et al., 2014).

4.2. Water Resources Management Implications

The concept of ES was developed to describe the benefits people obtain from ecosystems (Reid et al., 2005). It is therefore important that ES services be located in areas where they can readily be delivered to people. Results of this study showed a clear spatial unevenness in the distribution of ES across the state, implying that access to these services will also, likely not be balanced. The concentration of SWS hotspots in coastal and agricultural areas may also pose a challenge. As evidenced above, the same agricultural areas have low soil retention values implying that the quality of surface water will likely be affected. Siting of reservoirs to collect waters from coastal hotspots could also pose a challenge for management. Similarly, for a region highly dependent on groundwater sources, the GWR service is concentrated in a small portion of the state, implying accessibility will pose a challenge for over 80% of Texas with GWR ES values below the mean value. Also, this service is highly reliant on precipitation, making it susceptible to the negative impacts of climate change such as adverse drought conditions. Coldspots, particularly in the center of the State, are potential areas for restoration programs since the climate is not the limiting factor for the low total ES value. Lumbering rates across Texas are highest in high carbon storage ES value areas. The Piney woods ecoregion accounts for 73% of the State's wood-product production (Wall et al., 2019). Therefore, in addition to implementing measures that increase the acreage of high carbon storage areas, it is paramount that the existing hotspots be conserved.

4.3. Methodological Limitations and Opportunities

Technically, the evaluation of ES production areas based on an MCA approach is straightforward. Simply put, the MCA approach used in this study involved quantifying different alternatives, multiplying weights by the scores, and summing the weighted scores to get an aggregate ecosystem value for each production area. Because the services are valued in abstract terms, to ensure the required buy-in for such a structured process, the values that are attributed to the services should reflect the views and needs of stakeholders that benefit from the provision of ES. Stakeholders can have very different perspectives on the values of ES, based, among others, on their dependency upon specific services (Hein et al., 2006). A key strength of the MCA approach is its ability to factor in stakeholder input at several levels such as when choosing weighting criteria and or setting thresholds for values of coldspots and hotspots. Irrespective of the scale and type of services being evaluated, the lack of stakeholder participation in eliciting preferential values of ES can be a fundamental limitation of this methodology.

The study looked at four ES using four criteria to attach values of ES in their areas of production. However, the same areas provide other ES. Also, there are far more types of social, technical, institutional, and infrastructure criteria that can be considered. Consideration of more ES would highlight, further, the productive multiplicity of landscapes thus attracting investments in environmental management. Whereas this can easily be done at large institutional levels, it may be limited by financial and technical resources when initiated by small institutions.

Lastly, the potential services considered in this study were deduced from landscape processes that can be simulated by models. Hydrological models such as HAWQS have inherent limitations in simulating complex landscapes, like those with karst aquifers, especially when the model is run at a large spatial scale.

5. Conclusion

Valuation techniques used in ES as-assessments provide a mechanism for establishing baselines and measuring progress in watershed management programs. Also, ES assessments stand to benefit from landscape process-based modeling approaches, popular in IWM programs. The approach used in this study highlighted the advantages of this integrated approach. Hydrological tools used in this study quantified proxies of ES for a large area (for the entire State of Texas), yet at a fine-scale (sub-watershed level)—a feat not easily achievable when traditional small-scale field assessments are undertaken. Also, the use of MCA to value ES provided a simpler basis for identifying priority areas for resource management. Monetary valuation of the different non-market intangible services would have been more complicated.

Approach aside, the results of the study showed a high congruency of the existence and distribution of ES with climatic and land-use characteristics. The supply of individual and total ES varied significantly across space, although a high degree of co-location of high-value ES provision areas was noted in the eastern humid part of Texas. Conversely, total ES production was low in the arid west and the highly agriculturalized areas in the central part of the State. Therefore, both the distribution of rainfall and land-use activities markedly influenced the distribution of ecosystem service cold and hotspots. Maintaining sustainable ES levels in this region will require putting at the forefront, management of the impacts of climate variability and land-use changes.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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