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Towards ecosystem accounts for Rwanda: Tracking 25 years of change in flows and potential supply of ecosystem services

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Abstract

1. Rwanda, a small but rapidly developing central African nation, has undertaken development of natural capital accounts to better inform its economic development through the World Bank's Wealth Accounting and Valuation of Ecosystem Services (WAVES) Partnership. In this paper, we develop ecosystem service (ES) models to quantify ecosystem condition and physical supply components of ecosystem accounts in Rwanda from 1990 to 2015.
2. We applied the InVEST carbon storage, sediment delivery ratio, nutrient delivery ratio, and annual and seasonal water yield models to map changes in potential ES supply nationwide. We also quantified flows of sediment, water and nutrients to 96 hydroelectric dam, irrigation dam and water treatment plant sites.
3. Over a 25-year period, we found declines in all ES, which were most strongly driven by conversion of forests to cropland. Declines were most pronounced from 1990 to 2000 and 2010 to 2015; ES were relatively stable from 2000 to 2010 (with the exception of nutrient exports to water bodies, which jumped most sharply from 2000 to 2010). From 2010 to 2015, over 42% of Rwanda's water-use sites (representing 9% of the nation's hydroelectric generation capacity and 59% of its water treatment capacity) had upstream increases in sediment export and quick flow greater than the national average. Half of Rwanda's water treatment plants had upstream phosphorus exports greater than the national average.

4. Our results quantify nation-wide ES trends, their implications for key water-dependent industries, and the importance of protected areas in safeguarding ES flows and potential supply in Rwanda. They also provide data that can be integrated with existing land, water and economic accounts for Rwanda, as well as a baseline to inform development strategies that better link economic and environmental goals.

KEYWORDS
ecosystem accounting, ecosystem services, InVEST, System of Environmental and Economic Accounting (SEEA)

1 | INTRODUCTION

As the economies of many low-income African countries continue to grow, there is rising concern that current production and consumption models will undermine their ecological systems and limit the quality of growth on the continent (Egoh et al., 2012; IPBES, 2018; Marques et al., 2019). Governments throughout the region are committing to follow sustainable economic development pathways that maintain their natural capital to secure ecosystem services (ES) that are critical for livelihoods and economic development (Gaborone Declaration, 2019; UNEP, 2015). Across Africa, recent experience and economic models alike illustrate how 'green' investments can improve economic performance while conserving the natural resource base on which African economies and livelihoods depend (UNEP, 2015). Rwanda is among the countries making a commitment to green development within a rapidly growing economy. Rwanda has one of the higher GDP growth rates in Africa (World Bank, 2018a) with ambitions of transitioning into a middle-income country by 2020, as articulated in its 'Vision 2020' plan (Republic of Rwanda, 2000). The Government has pledged to pursue this growth through strategies that will maintain its natural capital through their commitment to the Gaborone Declaration, the national green growth and climate resilience strategy, establishment of a national natural capital committee steering committee, and demonstrating that the maintenance of natural capital is a critical component of its growth plans (Republic of Rwanda, 2011). Rwanda has made substantial progress in poverty reduction (from 58.9% of the population in 2000 to 38.2% in 2017; NISR, 2018a; World Bank, 2017); however, its growing population continues to exert further pressure on land use in favour of settlements and agriculture. These factors increase the need for innovative, science-based planning to promote more sustainable development trajectories. The Government is keen to adopt comprehensive green economy options in an effort to pursue more durable and equitable development pathways (Republic of Rwanda, 2011). However, the information and frameworks needed to assess those options are currently incomplete or lacking, as is the case in nearly all nations.

In May 2013, the Government of Rwanda approved the second phase of the Economic Development and Poverty Reduction Strategy (EDPRS II) to guide the country's development from 2013 through 2018 (Republic of Rwanda, 2013). The strategy was developed around thematic areas reflecting Rwanda's emerging development priorities, including (a) economic transformation, (b) rural development, (c) productivity and youth employment and (d) accountable governance. EDPRS II targeted 11.5% annual GDP growth; actual annual growth rates from 2010 to 2017 ranged from 4.7% to 8.9% (World Bank, 2018a). Land, water, forests and wildlife are the critical assets on which Rwandans rely for their livelihoods and support to industries such as energy, tourism and agriculture. Yet, under a business-as-usual scenario, targeted economic growth, increasing population, land scarcity and competing demand for water by various industries is likely to put additional pressure on ecosystems and the services they provide. For instance, development goals to increase energy generation capacity and production of priority crops (maize, wheat, rice, Irish potatoes, beans and cassava) under the national Crop Intensification Program are important components of the country's development strategy. Achieving both will be heavily dependent on the condition of land and water resources (Kathiresan, 2011; Republic of Rwanda, 2013), yet is also likely to impact ecosystem services; the extent of these impacts under different development trajectories is not yet clear. For instance, Rwanda's goal of increasing agricultural self-sufficiency through increased fertilizer use (Republic of Rwanda, Ministry of Agriculture, & Animal Resources, 2013) has not been evaluated against its potential consequences for water quality. Similarly, the future of tourism will depend on forest and wildlife conservation within the country's protected areas; Rwanda's model of revenue sharing with respect to tourism fees has been globally recognized for demonstrating how wildlife conservation and tourism can benefit local communities (Spenceley, Habyalimana, Tusabe, & Mariza, 2010), though challenges remain (Munanura, Backman, Hallo, & Powell, 2016). Rwanda's primary linked environment and development challenge is the management of existing resources to meet the needs of a growing population who depend on natural resources for every aspect of their livelihoods. As plans to implement development policies proceed, it will be important to understand how past and projected land-use changes will impact ecosystems and the services they provide for human livelihoods and different industries. However, the country currently lacks the evidence base needed to make decisions about where and how to develop without incurring negative trade-offs across industries or depleting the country's natural resource base and losing critical ES.

1.1 | Ecosystem service assessments and natural capital accounting for decision support

Decision-making about economic development and natural resource management can benefit from timely and accurate information about ES. Incorporating ES information into natural resource and economic planning can improve the overall value of benefits provided by the landscape and avoid unintended declines in ES provision (Guerry et al., 2015; Nelson et al., 2009; Polasky, Nelson, Pennington, & Johnson, 2011; Zheng et al., 2013). Similarly, incorporation of ES into national-level development planning can improve conservation and development outcomes and increase the likelihood of achieving sustainable development (Griggs et al., 2013; Miteva, 2019). Conversely, the lack of a unifying data and analytical framework can lead to resource management problems. For instance, agricultural, water or energy ministries may individually plan to use the same resources without considering each others' plans or their combined effects. Ecosystem accounts provide a unifying framework to understand resource availability and use by different industries, helping assess trade-offs to determine optimal development paths (Australian Bureau of Statistics, 2017; Keith, Vardon, Stein, Stein, & Lindenmayer, 2017; World Bank, 2016).

Although ES assessments can be used to inform natural resource management in several ways, their use in natural capital accounts is increasingly common (Vardon, Burnett, & Dovers, 2016). Natural capital accounts comprise the System of Environmental-Economic Accounts (SEEA) Central Framework (SEEA-CF, U.N. et al., 2014a) and the SEEA Experimental Ecosystem Accounts (SEEA-EEA, U.N. et al., 2014b). Rwanda is 1 of 16 nations engaged in the development of natural capital accounts through the Wealth Accounting and Valuation of Ecosystem Services (WAVES) Partnership (World Bank, 2018b). Rwanda has developed land and water accounts as part of the SEEA-CF (Republic of Rwanda, 2018, 2019), which provide time series data on land cover (1990–2015), land use and transaction values (2014–2015), and physical supply and use and asset tables for water (2012–2015); mineral accounts are in development (Stage & Uwera, 2018). Building on these accounts, ES data organized within the SEEA-EEA can broaden country's understanding of the effects of recent development policies, helping to guide future planning.

Like all accounts, the SEEA-EEA includes sets of tables built using rules that quantify linkages between natural resources and economic production. The SEEA-EEA includes multiple components, including ecosystem extent and condition accounts, physical and monetary supply and use tables, asset accounts, and thematic accounts for land, water, carbon and biodiversity (U.N. et al., 2014b; U.N., 2017). In understanding ES trends to inform the accounts, it is critical to distinguish the *potential supply* of ES that can be produced by ecosystems from their actual *flows* to beneficiaries that account for beneficiary locations in relation to ES supply and beneficiaries' levels of demand (Hein et al., 2016). Hein et al. additionally define the concepts of capacity and capability, both of which relate to the sustainability of ecosystem service use (capacity referring to the sustainable use level of multiple ES and capability the sustainable use of a single priority ES). Capacity and capability are most relevant for provisioning ES (capacity and flow are equivalent for regulating ES); we thus do not quantify them in this study. Others have provided similar but slightly different concepts to address differences between ES provision and flow in the SEEA-EEA (La Notte & Dalmazzone, 2018; La Notte, Vallecillo, Marques, & Maes, 2019). These two papers define 'ES potential' (equivalent to Hein et al.'s 'potential supply', a stock-aligned concept), plus multiple flow-aligned concepts: 'potential flows' as the maximum flow that can be sustained over time (equivalent to Hein et al.'s 'capacity' and 'capability'; La Notte et al. also use the term 'capacity' but unlike Hein et al. quantify it as a stock-aligned concept, based on its net present value), which differ from 'actual flows' that reflect current ES demand (equivalent to Hein et al.'s 'flow'). We use Hein et al.'s definitions for flows and potential supply of ES (equivalent to La Notte et al.'s 'actual flows' and 'potential', respectively) while noting that both sets of concepts are relatively new and neither have reached the consensus needed for incorporation into the formal SEEA-EEA guidance. The SEEA-EEA 2020 revision process, which is currently underway, aims to achieve such terminological consensus and formalization (U.N., 2018).

The SEEA-EEA Technical Recommendations (U.N., 2017) recognize that different ES classification systems can provide frameworks for consistently classifying ES in applications of the SEEA-EEA, including the Common International Classification of Ecosystem Services (CICES, Haines-Young & Potschin, 2018) and National Ecosystem Services Classification System (NESCS, USEPA, 2015). In our case, the modelled ecosystem services of carbon storage, sediment regulation, nutrient regulation and water yield correspond to CICES version 5.1 classes 'Regulation of chemical composition of atmosphere and oceans', 'Control of erosion rates', 'Regulation of the chemical condition of freshwaters by living processes' and the 'Water' division of Provisioning (Abiotic) services, respectively. In NESCS, by contrast, carbon storage is not considered an ecosystem service, as it is not a final ecosystem good or service; carbon would thus be included solely in a SEEA-EEA thematic carbon account (U.N., 2017). All of our modelled sediment regulation, nutrient regulation and water yield metrics would fall under the NESCS ecological end-product 'Water', with their 'Environment' determined by the ecosystem type at the location of their use, and the use and user dependent on the type of water user (e.g. water company or utility, hydroelectric power generator or agricultural irrigator; USEPA, 2015). Important terminological differences also exist between the SEEA-CF and the SEEA-EEA, for which SEEA-CF 'Natural water', a physical input moved from the environment into economic production, corresponds to 'Water provisioning' in the SEEA-EEA Technical Recommendations (U.N. et al., 2014a; U.N., 2017).

1.2 | Evidence-based management: Have Rwandan environmental policies protected natural capital?

Making economic planning decisions that protect ES requires evidence on the impacts that alternative land use and resource allocation have on ES. In many fields, including business, education, economic development and medicine, there is movement towards systematically assessing the benefits of various interventions and basing management decisions on this evidence (e.g. Pfeffer & Sutton, 2006; Slavin, 2002; Straus, Tetroe, & Graham, 2011). There have also been calls for evidence-based policy and management in conservation and resource management (Sutherland, Pullin, Dolman, & Knight, 2004). At present, such evidence is unevenly used to inform decisions affecting ES through land use or resource allocation (McKenzie et al., 2014). Evidence-based ecosystem management requires data and models capable of accurately predicting the provision of ES under alternative land use and resource allocation, plus a greater understanding of how policy interventions impact the environment (Karamage et al., 2017). Models are necessary for predicting impacts of potential decisions (Schröter, Remme, Sumarga, Barton, & Hein, 2015), and their validation with field data can instil confidence in their predictive ability. Models can also help to quantify recent historical baselines for ES, that is, how future interventions may lead to divergence from recent trends. Additionally, where available, official statistics can also inform ecosystem accounts, particularly for provisioning ecosystem services (Vallecillo et al., 2019). A retrospective analysis of ES trends aligns well with the goals of the SEEA-EEA, which tracks ES trends and their contributions to specific economic industries, households and government.

Over the past two decades, the Government of Rwanda has enacted policies and legislation governing land use, to ensure sound land use and environmental protection for sustainable development. Ecosystem accounts can be used to show how effective these policies have been in conserving natural capital and ES. For instance, soil erosion control, increased soil fertility and environmental protection have been emphasized in the major national development frameworks, particularly in Vision 2020 and EDPRS II (Republic of Rwanda, 2000, 2013). Recognizing how high demographic pressure has led to the occupation of marginal areas and rapid soil degradation in fragile ecosystems, Vision 2020 stated clearly that ‘to ensure sustainable development, Rwanda will implement adequate land and water management techniques, coupled with a sound biodiversity policy’ (Republic of Rwanda, 2000, p. 20). Various laws passed over the last two decades govern soil conservation, land management and general environmental protection, with particular emphasis on erosion control to support more sustainable agriculture.

Finally, the Government of Rwanda has been working with national and international partners to implement forestry and soil conservation programmes that contribute towards meeting the EDPRS II and Vision 2020 goals. For example, since 2000 the Belgian Development Agency has worked with the Rwanda Natural Resource Authority (RNRA; now the Rwanda Water and Forestry Authority) to reduce deforestation and poverty by improving the management of existing woodlots and reforesting degraded and sensitive lands (Belgian Development Agency, 2012). The World Bank is working with the Rwanda Environment Management Authority (REMA) as part of the Landscape Approach to Forest Restoration and Conservation (LAFREC) project to develop sustainable forest management objectives for the Gishwati Forest landscape. REMA also compiles a biennial State of the Environment report that publishes various indicators on the nation's environment (REMA, 2015, 2017). Various NGOs are also working with partners throughout the country to address Rwanda's environmental, social and economic challenges by selectively raising naturally occurring trees with economic value. Despite these efforts, a lack of nationally consistent data and methods has limited the ability to assess the impact of these investments and policies on ES that are critical to the Rwanda's economic development.

In this paper, we used ES models to quantify trends in service provision in Rwanda from 1990 to 2015, populating ecosystem condition and physical supply tables in the SEEA-EEA. We used Rwanda's land accounts (Republic of Rwanda, 2018) as an ecosystem extent account, and do not at this time quantify monetary accounts (U.N. et al., 2014b). This time period encompasses both the period of extreme instability in Rwanda in the 1990s and the greater stability it has experienced starting in the 2000s. Diverse modelling methods can be applied in ecosystem accounting (Schröter et al., 2015); in this case, we used the Integrated Valuation of Ecosystem Services Tradeoffs (InVEST) tool (Sharp et al., 2016), building on preliminary modelling work done by the Natural Capital Project to apply these models in Rwanda and neighbouring Uganda (Gourevitch et al., 2016). We modelled carbon storage, sediment regulation, nutrient regulation, and annual and seasonal water yield. We summarized results for the nation, its five provinces, 30 districts, and four national parks, quantifying potential supply of these ES. Additionally, for sediment regulation and water yield, we quantified changes in ES flows (Hein et al., 2016) in watersheds upstream of irrigation dams, hydroelectric power dams and water treatment plants. For nutrient regulation, we quantified ES flow changes upstream of water treatment plants, a water user for whom excess nutrients may be problematic. This enables us to identify locations where changing land cover and agricultural practices may affect water supplies for hydroelectric power, irrigation and domestic supply. In these locations, future development plans may need to address how changes to water quantity, quality and timing may impact water security and economic development. Our work thus illustrates the application of ecosystem accounts to evaluate sustainability of ES in a small, rapidly changing African nation illustrative of the continent's rapid economic, population and environmental change (Egoh et al., 2012; IPBES, 2018).

2 | MATERIALS AND METHODS

2.1 | Study area

Rwanda is a landlocked country situated in the central African highlands with a total surface area of 26,338 km^2 and some 1,385,000 ha

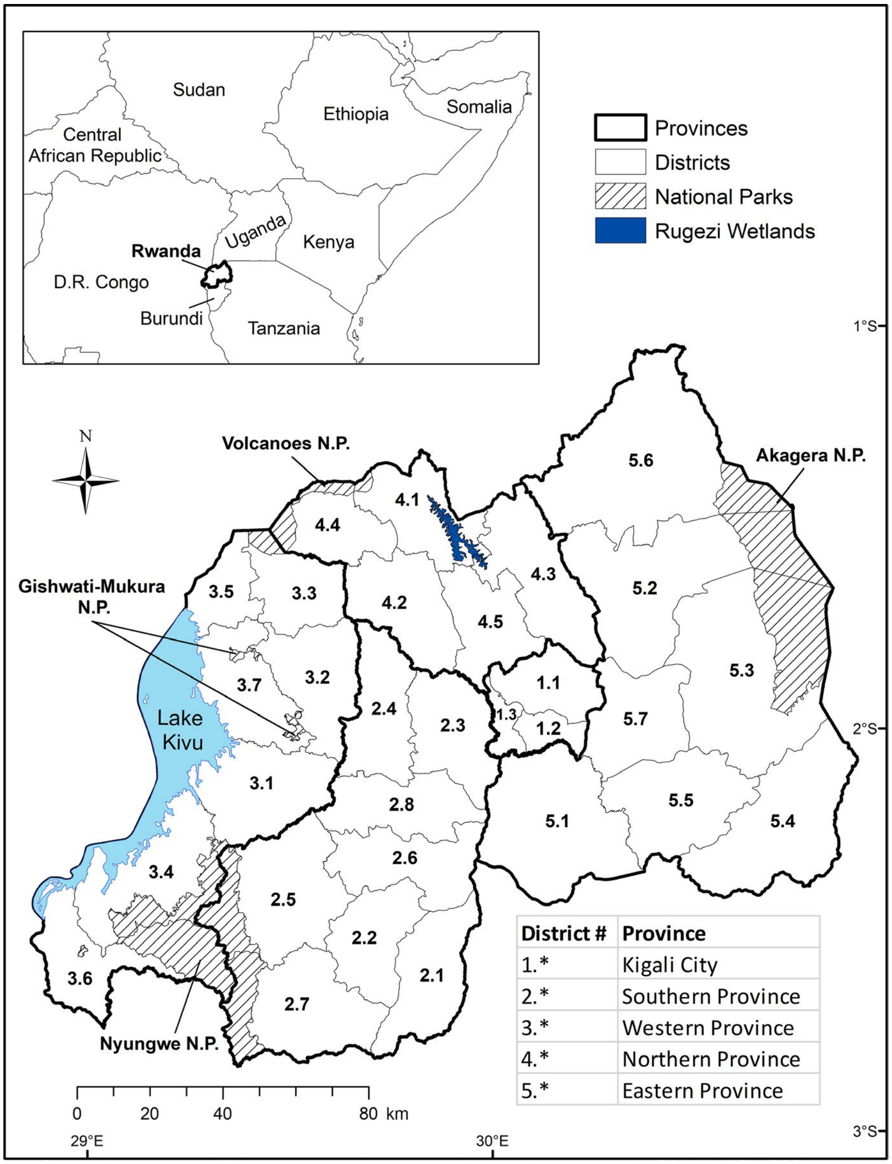


FIGURE 1 Study area map. District numbers are used to organize district-scale ecosystem accounts by province (Supporting Information Appendix D)

of potentially arable land (Figures 1 and 2). With a population of 12.2 million people and 494 people per km^2, Rwanda is the most densely populated country in Africa (World Bank, 2018a). Rwanda's population is predicted to more than double to 26 million by 2050, with population density increasing to 987 people per km^2 (Republic of Rwanda, 2011). The majority of the population farms small hillside plots in the rural areas, though urbanization is increasing at 4.4% per year.

From east to west, there is a general topographic trend of increasing elevation, greater local relief and increasing slope steepness. Agricultural production is concentrated in the central and western portions of the country where there is more rainfall, despite the prevailing hilly and mountainous terrain. Additionally, the relatively fertile soils found in the west, especially the volcanic soils in the northwest, have attracted generations of Rwandan farmers (Clay & Lewis, 1990). Because of this farming pattern, half of all fields are on slopes greater than 18%. Thus, if not properly managed, much of Rwanda's farmland has the potential for excessive soil loss. Conversion of land from forest and woodland to cropland has been the most notable trend in Rwanda's land cover, particularly from 1990 to 2000 and 2010 to 2015 (Republic of Rwanda, 2018, Figure 2).

2.2 | Selection of ecosystem services for modelling

Through a series of working group meetings convened by the Science for Nature and People Partnership (SNAPP) from September 2015 through March 2017, we defined a list of ES, methods, and data sources and developed and refined ES models together with stakeholders. The working group included representatives from the Government of Rwanda, civil society (i.e. the Wildlife Conservation Society-Rwanda), and technical experts from the World Bank, US Geological Survey, and Rwandan and US academics. Carbon storage, sediment regulation, nutrient regulation and water yield were identified as ES that would add value for decision-making and were feasible

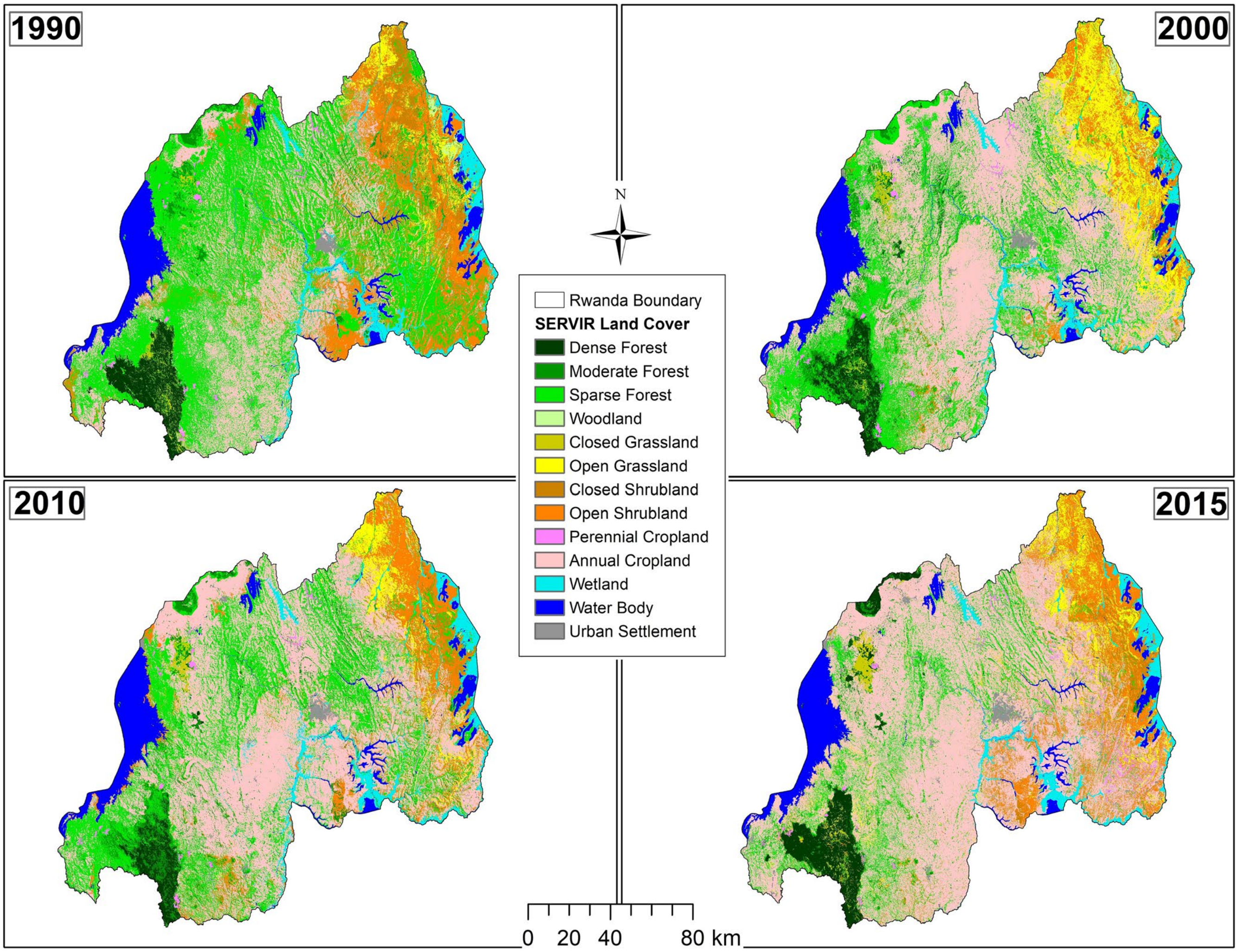


FIGURE 2 Rwanda Scheme II land cover, 1990–2015. Source: Regional Center for Mapping of Resources for Development

to quantify using existing data. Flood regulation was of interest to the government, but we lacked the needed input and calibration data for its modelling. As described below, we did run the InVEST seasonal water yield model, which estimates quick flow – runoff that occurs during or soon after rain events. Although not a flood model, it provides somewhat of a proxy for how the landscape's capacity for rainfall infiltration and flood regulation are changing over time.

2.3 | Modelling approach

We used the InVEST 3.3.3 modelling software (Sharp et al., 2016) to quantify carbon storage, sediment regulation (sediment delivery ratio (SDR) model), nutrient regulation (nutrient delivery ratio (NDR) model), and annual and seasonal water yield in Rwanda for the years 1990, 2000, 2010 and 2015, based largely on land-cover data generated by the Regional Center for Mapping of Resources for Development (RCMRD, http://geoportal.rcmrd.org/). Further details about the model data sources and parameterization are included as Supporting Information; a brief description of each InVEST model follows. InVEST's carbon storage model uses a lookup table to pair land-cover data with estimated carbon pools in vegetation, soils and woody debris for each land-cover type. Its SDR model estimates sediment retention and export by pairing the Universal Soil Loss Equation (Renard, Foster, Weesies, McCool, & Yoder, 1997) with a connectivity index to model sediment export and retention. The NDR model uses land-cover specific estimates of nitrogen and phosphorus loading and potential nutrient uptake, combined with the SDR model's connectivity index to quantify nutrient export to downstream water bodies. NDR model outputs include nutrient load (kg N and P applied to or potentially released from each grid cell) and export (N and P reaching downstream water bodies). Nutrient retention (N and P retained by soils and vegetation that is prevented from reaching water bodies) can be estimated as the difference between nutrient loads and nutrient exports, but the model does not calculate nutrient retention on a grid cell basis. The annual water yield model uses the Budyko curve method (Fu, 1981) to model actual evapotranspiration (AET), then subtracts AET from mean annual precipitation to quantify annual water yield. Finally, the seasonal water yield model estimates quick flow (runoff during and immediately following storm events, which can cause problems with flooding, water quality and dry-season water availability; estimated using the Curve Number method) and local recharge (which becomes available as baseflow that supports dry-season river flows; calculated by subtracting AET plus quick flow from precipitation). We conducted our analysis at 30 m spatial resolution. More details are included as Supporting Information, including spatial data inputs and literature sources for model parameterization (Supporting Information Appendix A), methods for deriving soil erosion model support (P) factors based on terracing data for Rwanda (Ndabamenye et al., 2013; Supporting Information Appendix B), and water model calibration (Supporting Information Appendices A and C); all results are available as a US Geological Survey data release (Bagstad et al., 2019).

We summarized results for all five provinces and 30 districts in Rwanda, as well as for the nation's four national parks. We also used spatial data for existing and planned water infrastructure use locations, specifically 33 irrigation dams, 24 hydroelectric dams and 39 water treatment plants to distinguish between the *potential supply* of water and sediment regulation for the entire nation and *actual flows* that reach different water users (as well as actual flows of nutrient exports to water treatment plants; Hein et al., 2016). We then evaluated changes in sediment export, phosphorus exports (phosphorus being the nutrient typically responsible for freshwater eutrophication) and quick flow from 2010 to 2015 within watersheds upstream of water-use points. This analysis excludes ES change in small areas in Uganda that lie upstream of some Rwandan water users. To do this, we used ArcGIS to (a) snap each dam or treatment plant site to its nearest river flow accumulation line, (b) delineate upstream watersheds for each site and (c) sum annual water yield, quick flow, local recharge, sediment retention, sediment export and phosphorus export occurring within each upstream watershed. Changes in these values over time can indicate changes in the quality, quantity and timing of water received by each user. While this analysis does not explicitly quantify ES demand (which would require spatially explicit water-use data and further information about the effects of sediment and nutrients on different water users), it does address the difference between potential supply and actual flows of water-based ES. Finally, we used ArcGIS to estimate additions and reductions in each ES for the different time periods and to summarize changes in ES by land-cover type (i.e. ecosystem extent) to populate ecosystem condition and biophysical supply tables for the ecosystem accounts (U.N. et al., 2014b). Our final tables include ecosystem extent (derived from Republic of Rwanda, 2018), ecosystem condition (nation-wide nitrogen and phosphorus load and export, sediment export), potential supply (nation-wide carbon storage, annual and seasonal water yield, sediment retention) and physical supply (annual and seasonal water yield, sediment and nutrient delivery parameters upstream of water users).

3 | RESULTS

Nationally, most ES experienced relatively steep declines from 1990 to 2015, with a period of relative stability between 2000 and 2010 (Figure 3). Carbon storage, sediment retention and local recharge declined while indicators of ES degradation – sediment export and quick flow (the inverses of sediment retention and local recharge, respectively) – increased rapidly over this period. Nutrient loading, retention and exports jumped most substantially from 2000 to 2010, a period during which fertilizer inputs increased by 590% (Republic of Rwanda, Ministry of Agriculture, & Animal Resources, 2013).

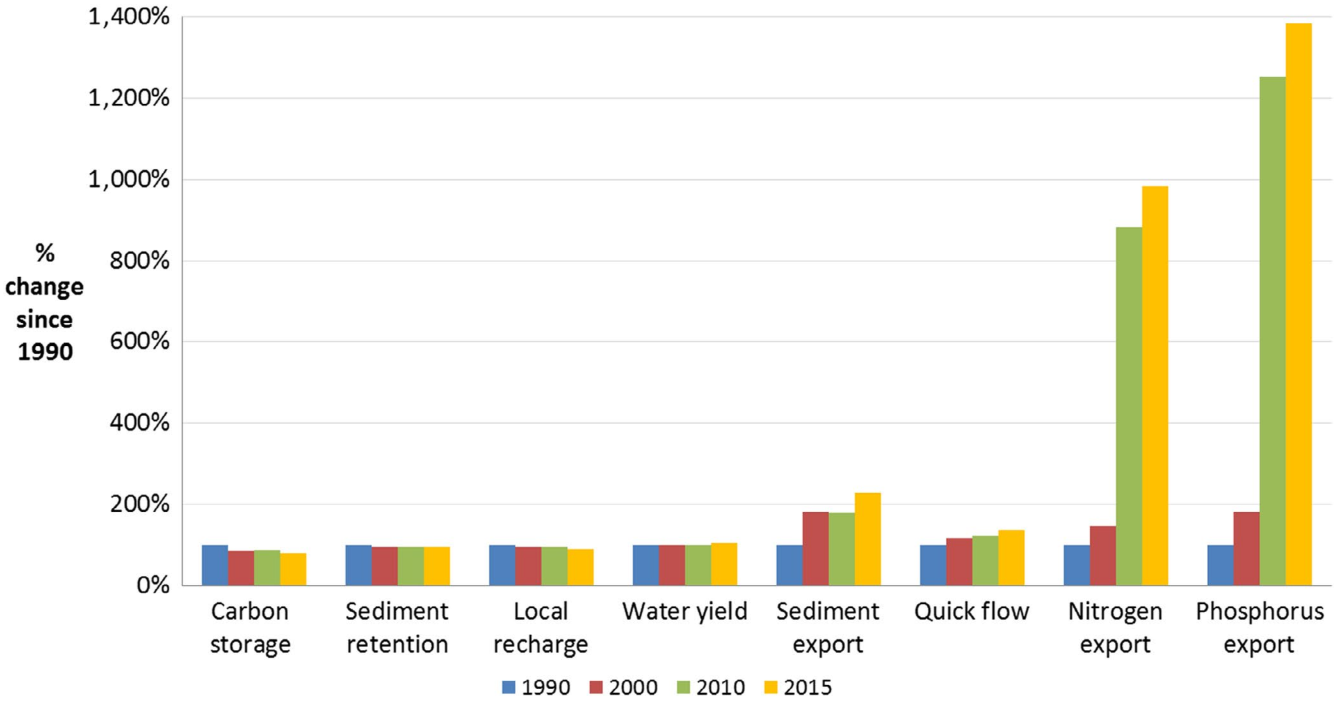


FIGURE 3 Ecosystem service trends for Rwanda, 1990–2015

TABLE 1 Ecosystem extent (A), condition (B), potential supply (C) and physical supply (D) tables for Rwanda [Correction added after online publication on 7 January 2020: numbers altered to correct misplaced commas]

A. Ecosystem extent (ha)

	Ecosystem types (land cover)												
Year	Dense forest	Moderate forest	Sparse forest	Woodland	Closed grassland	Open grassland	Closed shrubland	Open shrubland	Perennial cropland	Annual cropland	Wetland	Water body	Urban
1990	85,827	71,282	943,980	9,922	4,263	70,750	83,734	355,986	10,653	618,480	115,945	153,427	11,632
2000	63,064	148,898	538,383	7,967	12,337	233,393	846	149,821	11,033	1,121,563	79,932	153,491	13,842
2010	48,329	123,335	581,245	472	13,382	81,861	35,769	245,939	10,985	1,110,862	104,780	155,805	20,642
2015	114,489	47,042	268,292	0	31,384	116,827	49,469	279,445	33,947	1,306,551	83,359	150,040	36,176

B. Ecosystem condition

		Ecosystem types (land cover)													
Metric	Year	Dense forest	Moderate forest	Sparse forest	Woodland	Closed grassland	Open grassland	Closed shrubland	Open shrubland	Perennial cropland	Annual cropland	Wetland	Water body	Urban	Total
Sediment export (kT)	1990	7	38	1,158	18	41	89	85	534	14	4,252	38	1	16	6,289
	2000	14	208	939	19	141	381	0	262	15	9,068	12	1	19	11,080
	2010	3	129	1,001	0	149	107	73	450	14	8,099	37	2	29	10,094
	2015	34	116	1,242	0	320	377	160	654	41	11,004	17	0	62	14,027
Nitrogen load (T)	1990	154	140	1,868	15	15	261	321	1,297	29	1,672	235	11	75	6,093
	2000	114	289	1,071	13	45	893	3	564	30	3,060	158	12	89	6,340
	2010	88	349	2,393	1	69	452	206	1,271	198	19,259	285	27	165	24,764
	2015	215	128	996	0	140	579	213	1,445	602	24,173	196	16	270	28,973
Nitrogen export (T)	1990	0	2	64	1	4	16	21	98	15	397	79	2	29	728
	2000	1	10	52	1	13	64	0	44	14	802	47	2	29	1,077
	2010	1	34	285	0	25	36	21	131	91	5,683	77	5	52	6,441
	2015	2	10	109	0	37	64	21	154	125	6,519	50	5	84	7,181
Phosphorous load (T)	1990	1	5	135	1	2	33	40	178	14	728	11	1	1	1,149
	2000	2	24	128	1	6	132	0	78	15	1,391	7	2	1	1,787
	2010	1	69	740	0	17	118	58	316	99	9,542	51	9	19	11,040
	2015	4	24	281	0	26	126	35	337	298	12,072	15	7	15	13,240
Phosphorous export (T)	1990	0	0	25	0	1	2	3	16	7	193	3	0	0	250
	2000	0	4	23	0	2	11	0	7	7	394	2	0	0	450
	2010	0	16	139	0	8	12	7	43	46	2,847	10	2	4	3,134
	2015	1	4	48	0	8	19	4	45	62	3,268	3	2	4	3,468

(Continues)

TABLE 1 (Continued)

C. Potential supply														
		Ecosystem types (land cover)												
Metric	Year	Dense forest	Moderate forest	Sparse forest	Woodland	Closed grassland	Open grassland	Closed shrubland	Open shrubland	Perennial cropland	Annual cropland	Wetland	Water body	Urban	Total
Carbon storage (MT)	1990	35	25	277	3	1	11	16	67	2	89	83	14	1	623
	2000	25	50	157	2	2	36	0	28	2	158	57	14	2	533
	2010	19	42	170	0	2	13	7	46	2	156	75	14	2	548
	2015	46	16	76	0	5	18	9	52	6	183	64	14	4	492
Sediment retention (kT)	1990	31,247	24,290	220,331	873	1,777	3,837	3,181	22,139	1,505	96,764	1,603	211	442	408,201
	2000	24,060	52,598	132,295	830	5,113	11,368	10	9,116	1,470	165,249	428	262	521	403,319
	2010	16,622	42,188	155,840	12	4,950	3,337	2,583	16,264	1,526	158,284	1,217	520	732	404,075
	2015	49,779	18,522	87,095	0	10,850	9,749	5,168	17,496	3,330	196,245	566	174	1,426	400,401
Water yield (1,000 m^3)	1990	589,910	362,588	2,920,910	19,907	32,846	94,671	155,069	814,394	70,543	1,986,039	21,575	4,007	21,361	7,093,821
	2000	429,963	670,132	1,805,048	17,552	97,603	273,344	1,703	337,108	73,485	3,218,491	12,621	5,201	29,632	6,971,882
	2010	346,036	625,886	1,772,860	849	96,953	94,291	72,020	608,115	73,252	3,356,034	19,383	6,506	47,449	7,119,634
	2015	819,223	213,844	859,918	0	222,363	187,680	148,974	645,042	116,216	4,068,392	3,765	1,951	91,400	7,378,769
Local recharge (1,000 m^3)	1990	554,304	368,215	2,619,157	5,776	28,604	33,697	45,061	275,008	35,732	1,108,721	8,007	3,015	3,126	5,088,423
	2000	405,183	661,560	1,639,933	4,508	83,674	108,148	567	119,573	37,118	1,724,531	4,607	3,552	4,895	4,797,848
	2010	334,065	631,518	1,573,278	184	82,818	33,432	24,094	230,803	37,004	1,825,947	6,453	4,302	8,922	4,792,822
	2015	765,498	213,355	747,399	0	187,228	97,897	68,201	163,088	43,616	2,196,800	3,281	2,542	19,484	4,508,390
Quick flow (1,000 m^3)	1990	22,493	27,292	443,558	5,993	6,336	32,934	50,600	214,656	26,792	852,562	571,471	114,563	17,450	2,386,700
	2000	18,626	67,809	322,216	4,230	20,052	127,891	723	103,299	28,299	1,550,445	399,701	112,223	21,791	2,777,304
	2010	11,960	46,185	307,168	510	21,115	41,263	22,661	165,645	28,003	1,597,340	528,702	120,380	33,411	2,924,343
	2015	36,907	20,963	183,022	0	48,980	76,669	38,150	185,949	46,285	1,962,462	473,449	108,640	60,094	3,241,573

D. Physical supply														
		Ecosystem types (land cover)												
Metric	Year	Dense forest	Moderate forest	Sparse forest	Woodland	Closed grassland	Open grassland	Closed shrubland	Open shrubland	Perennial cropland	Annual cropland	Wetland	Water body	Urban	Total
Sediment export (kT)	2010	1	98	539	0	89	19	13	116	5	3,814	17	0	20	4,730
	2015	8	44	481	0	177	162	29	203	18	4,667	11	0	37	5,837
Sediment retention (kT)	2010	2,416	17,719	55,952	0	3,059	590	439	4,327	558	77,587	539	56	475	163,716
	2015	14,926	7,272	36,138	0	5,915	4,081	918	5,453	1,418	85,336	344	65	821	162,687
Nitrogen export (kg)	2010	37	5,363	44,762	0	12,573	2,052	3,373	12,854	11,844	541,949	3,663	684	23,399	662,551
	2015	89	376	4,972	0	14,158	4,285	335	15,677	20,938	668,777	1,319	490	29,755	761,170

(Continues)

TABLE 1 (Continued)

D. Physical supply															
		Ecosystem types (land cover)													
Metric	Year	Dense forest	Moderate forest	Sparse forest	Woodland	Closed grassland	Open grassland	Closed shrubland	Open shrubland	Perennial cropland	Annual cropland	Wetland	Water body	Urban	Total
Phosphorus export (kg)	2010	17	2,545	21,836	0	3,761	894	1,546	5,424	5,946	270,650	783	294	988	314,683
	2015	29	119	1,640	0	2,207	1,068	89	4,418	10,445	334,818	318	219	743	356,113
Water yield (1,000 m^3)	2010	83,018	292,299	737,101	0	72,264	17,657	11,474	151,230	29,449	1,791,486	6,507	1,853	29,568	3,223,905
	2015	295,635	98,764	413,318	0	138,930	70,862	30,506	167,483	55,948	1,982,215	2	235	52,717	3,306,614
Local recharge (1,000 m^3)	2010	80,112	286,796	632,140	0	62,330	6,385	3,619	76,083	14,163	989,737	2,391	938	5,431	2,160,124
	2015	276,191	98,419	378,212	0	117,440	45,105	17,006	45,008	17,023	1,058,481	1,393	361	10,189	2,064,829
Quick flow (1,000 m^3)	2010	2,676	21,733	130,934	0	15,099	7,398	4,957	36,428	11,763	821,860	74,073	23,347	20,651	1,170,919
	2015	12,148	8,628	65,692	0	29,577	23,411	6,995	40,119	23,176	961,083	50,490	25,714	34,008	1,281,041

Increases in annual water yield indicate less evapotranspiration (i.e. water regulation through vegetation) and more runoff, but their implications are somewhat ambiguous. Analysis of local recharge and quick flow thus provides a more complete view of changes in water yield (Sharp et al., 2016). Ecosystem condition tables (quantifying nutrient loads and exports and sediment export), potential supply tables (that account for total production of potential benefits to people) and physical supply tables (showing ES use and flows to people, U.N. et al., 2014b) for all ES, with summaries for the nation, provinces, districts and protected areas are included as Supporting Information Appendix D and shown below for the nation (Table 1).

Key land-cover (i.e. ecosystem extent) trends from 1990 to 2015 that underlie ES changes in Rwanda include loss of forests and woodlands (−61.3%), shrublands (−25.2%) and wetlands (−28.1%), and increasing cover of grasslands (+97.6%), croplands (+113.1%) and urban areas (+211%, Republic of Rwanda, 2018). ES changes typically reflect trends in the extent of these ecosystems (shown in the leftmost bar for each ecosystem type in Figure 4). However, ecosystem extent is a better predictor for simple models like carbon sequestration than for more complex models like sediment and nutrient retention, which depend not just on land cover but also on soils, topography, climate and agricultural practices.

3.1 | National, provincial and district-level potential ecosystem service supply changes

Total carbon storage nationwide (including above-ground, below-ground, soil and woody debris carbon) declined from 627.0 MT in 1990 to 495.3 MT in 2015, with a slight increase from 2000 to 2010 (Figures 5 and 6). On a per hectare basis, carbon stocks fell from 247.4 T/ha to 195.4 T/ha over this period. Carbon storage was greatest in the country's Eastern, Southern and Western Provinces, which include wetlands and substantial protected areas (Akagera National Park (NP) in the east, with extensive natural grasslands, shrublands, and wetlands, and Nyungwe NP in the southwest with its extensive forest). At the district level, carbon storage ranged from 150 to 257 T/ha, with the smallest values in cropland-dominated Gisagara District and the largest in Rusizi, which contains forested areas within Nyungwe NP (Supporting Information Appendix E).

Nationally, modelled sediment export more than doubled from 6.3 to 14.0 MT/year from 1990 to 2015. On a per-hectare basis, sediment export increased from a mean of 2.5 T/ha*year to 5.5 T/ha*-year over our study period. Conversely, sediment retention declined steadily from 408.5 to 400.8 MT from 1990 to 2015. Generally, sediment export was greatest in the Northern and Western Provinces, particularly in the higher-elevation districts, and lowest in the flatter Eastern Province (Figures 5 and 6; Supporting Information Appendix E). On a per hectare basis, sediment export ranged from 0.8 to 18.3 T/ha*year in Bugesera and Nyabihu districts, respectively.

Modelled nitrogen exports in Rwanda increased from 730 to 7,183 T from 1990 to 2015; phosphorus exports during this period rose from 250 to 3,469 T. These trends are driven by increases in nutrient loads (from 6.1 to 29 kT N and 1.2 to 13.2 kT P from 1990 to 2015). Nitrogen and phosphorus retention by ecosystems (the difference between nutrient loads and exports) similarly rose during this period. Over time, however, ecosystems retained a smaller percentage of the nutrient loads (from 88% and 78% of nitrogen and phosphorus loads in 1990 to 75% and 74% of the same nutrients in 2015). Nutrient export was greatest both in total and per hectare terms for the Southern Province (Figures 5 and 6; Supporting Information Appendix E); regions with large extents of cropland and greater slope and rainfall typically had the highest nutrient export levels.

We estimated nation-wide water yield at 7.14 billion m^3 in 1990, which increased to 7.42 billion m^3 by 2015. While small, these water yield increases are not necessarily desirable. Less evapotranspiration leaves more water available for surface and groundwater resources, but this water may runoff quickly, contributing to water quality problems and reduced groundwater recharge. To address these limitations, the seasonal water yield model results (described below) add additional nuance to our analysis of hydrologic ES. Water yield in Rwanda strongly follows the country's rainfall gradient (Figure 5), with greater precipitation and water yield in the mountainous western part of the country than in the east. District-level changes were generally characterized by small increases (<10% change per time period), with the exception of districts in the Eastern Province, many of which saw decreases in water yield from 1990 to 2000 then increases from 2000 onward, largely owing to large-scale transitions between shrublands and grasslands in those years (Figure 6; Supporting Information Appendix E).

Nationally, local recharge (like annual water yield) follows a strong east-west gradient, with greater recharge in the rainier west than in the east (Figure 5). Changing land cover led to increases in quick flow and decreases in local recharge from 1990 to 2015, with the greatest changes occurring from 1990 to 2000 and 2010 to 2015 (Figure 6). Local recharge nationally declined from 5.07 to 4.49 billion m^3 from 1990 to 2015 while quick flow increased from 2.39 to 3.23 billion m^3 over this period. As a result, the percentage of water yield as quick flow increased from 32.0% to 41.8% from 1990 to 2015. At the province and district level, changes in quick flow and local recharge were somewhat more varied (Figure 4; Supporting Information Appendix E). Quick flow steadily increased over time in the Southern and Western Provinces and saw slower or more uneven increases elsewhere.

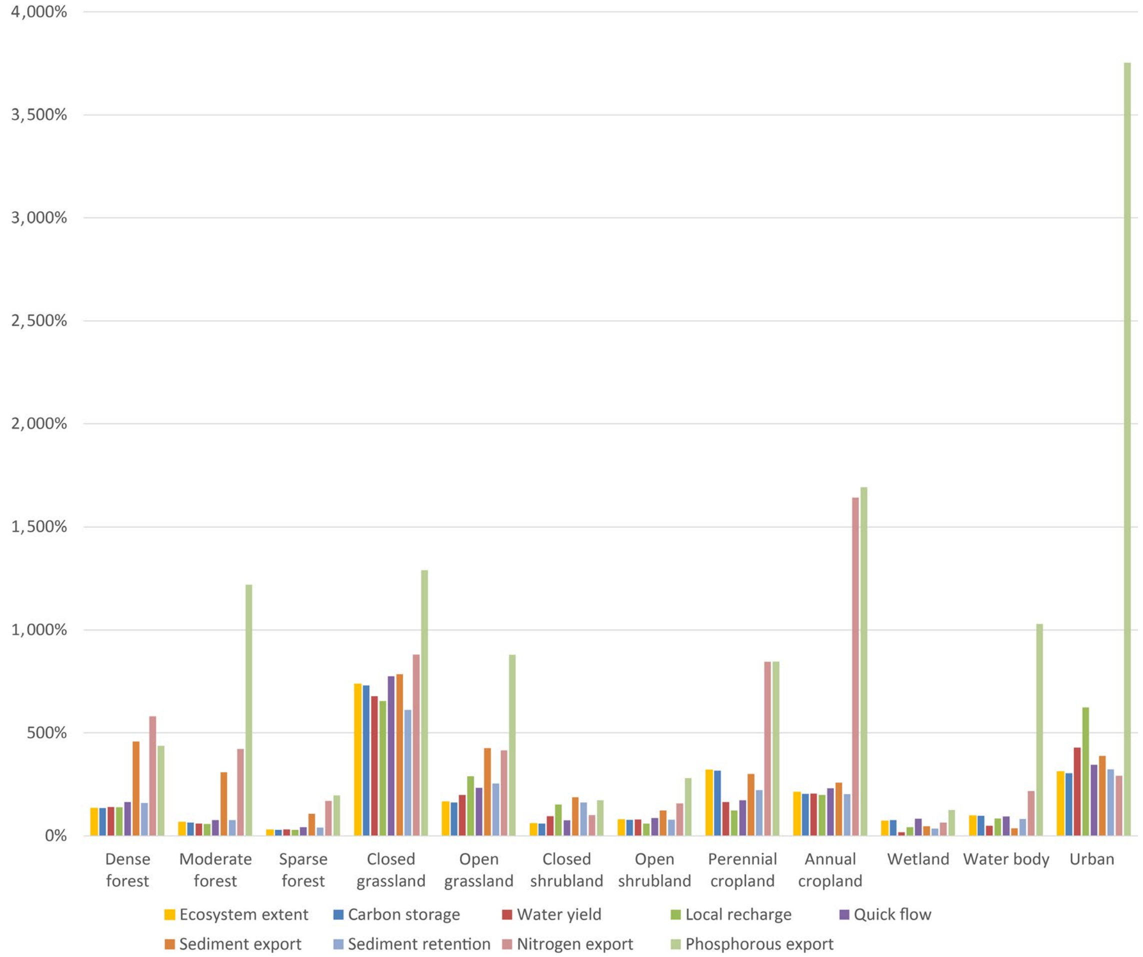


FIGURE 4 Changes in ecosystem extent, condition and potential ecosystem service supply for Rwanda by ecosystem (land cover) types, 1990–2015 (1990 = 100%)

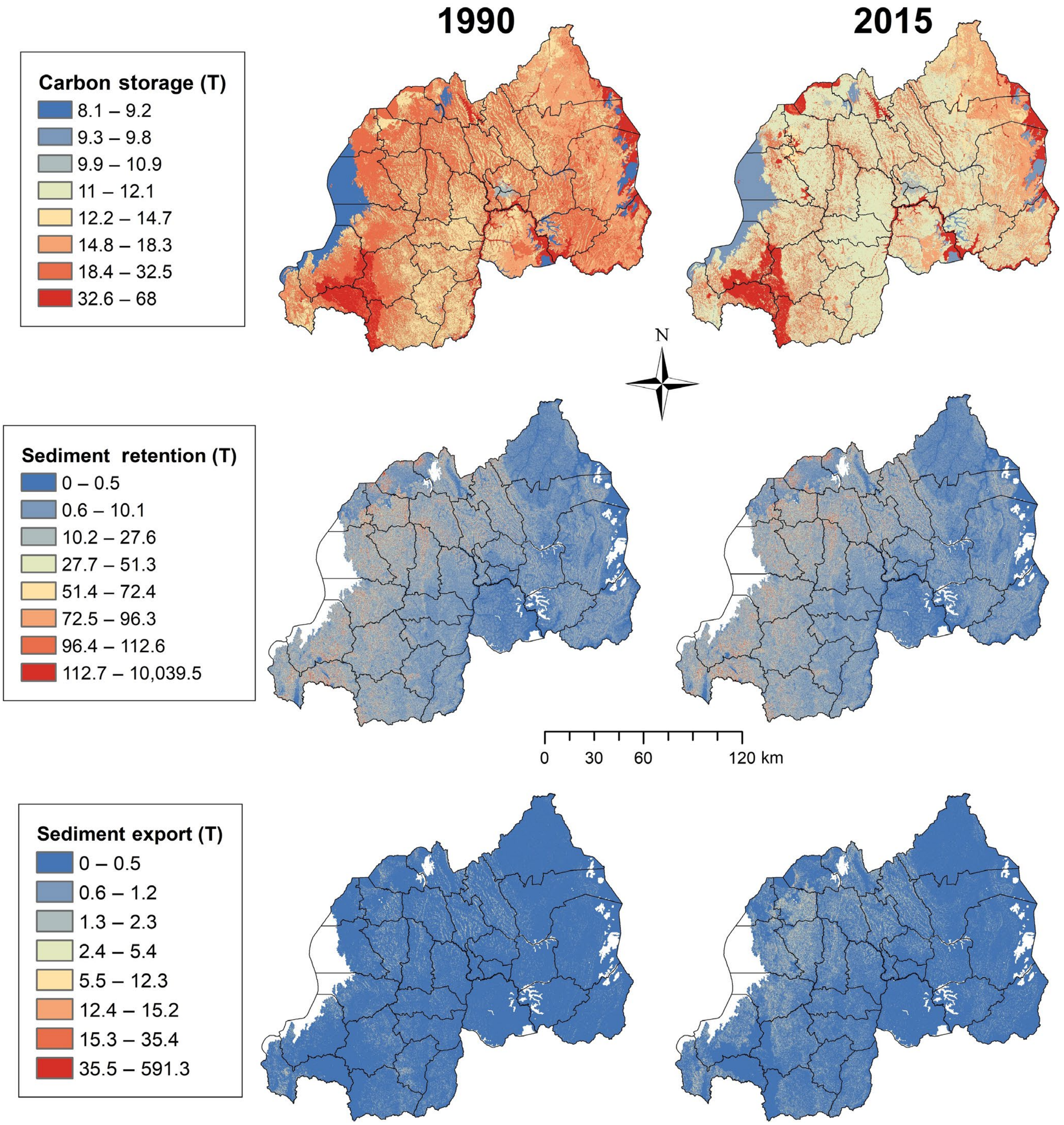


FIGURE 5 Changes in ecosystem service metrics for Rwanda for 1990 and 2015, showing district boundaries

3.2 | Potential ecosystem service supply changes in protected areas

Nyungwe NP saw a small decline in carbon storage throughout the study period, from 40.0 to 38.7 MT (Figure 7). Akagera NP witnessed a decline in carbon storage from 35.4 to 29.6 MT from 1990 to 2000, but a rebound to 33.2 MT by 2015. Volcanoes NP saw a similar decline then rebound in carbon storage, from 5.4 to 5.1 to 6.3 MT in 1990, 2000, and 2015, respectively. Finally, Gishwati-Mukura NP saw a decline in carbon storage from 1.14 to 1.08 MT from 1990 to 2000 (reflecting forest loss, Ordway, 2015), then an increase to 1.23 MT in 2015.

Sediment export from protected areas was much lower than the national average on a per-hectare basis (0.9 vs. 5.5 T/ha*year). Substantial increases in sediment export occurred in Gishwati-Mukura NP (+256% from 1990 to 2015, largely driven by deforestation in the 1990s (Ordway, 2015, with subsequent recovery; Figure 7), Akagera NP (+37% from 1990 to 2015, with greater

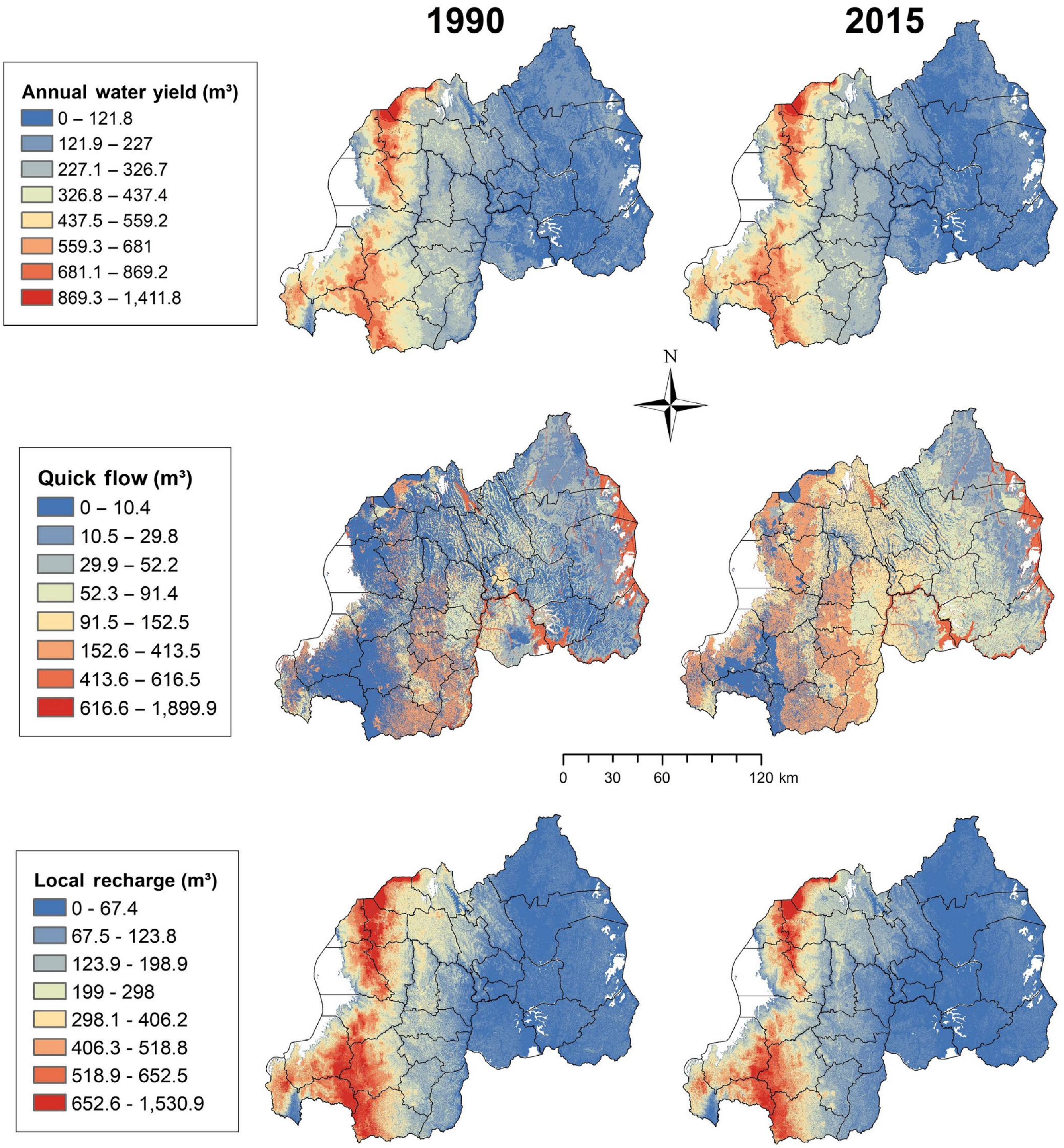


FIGURE 5 (Continued)

sediment export occurring in years when grasslands were more dominant than shrublands) and Nyungwe NP (+137%).

Nutrient exports from protected areas were minor (<1% of the national total in 2015), particularly on a per-hectare basis. While forests, grasslands and shrublands release nutrients, they do so at a much lower rate than croplands and urban areas. Temporary increases in nutrient exports (e.g. for Gishwati-Mukura and Volcanoes NP in 2010 and Nyungwe NP in 2015) appear to be caused by a small number of cropland cells found within the park boundaries. These may indicate small-scale encroachment of croplands into protected areas or classification errors in the land-cover datasets.

Akagera NP saw an 18.6% increase in water yield from 1990 to 2015 while the other three national parks had minimal (1%–2%) changes in water yield over the study period (Figure 7). With greater forest cover and lacking urban and agricultural land, national parks

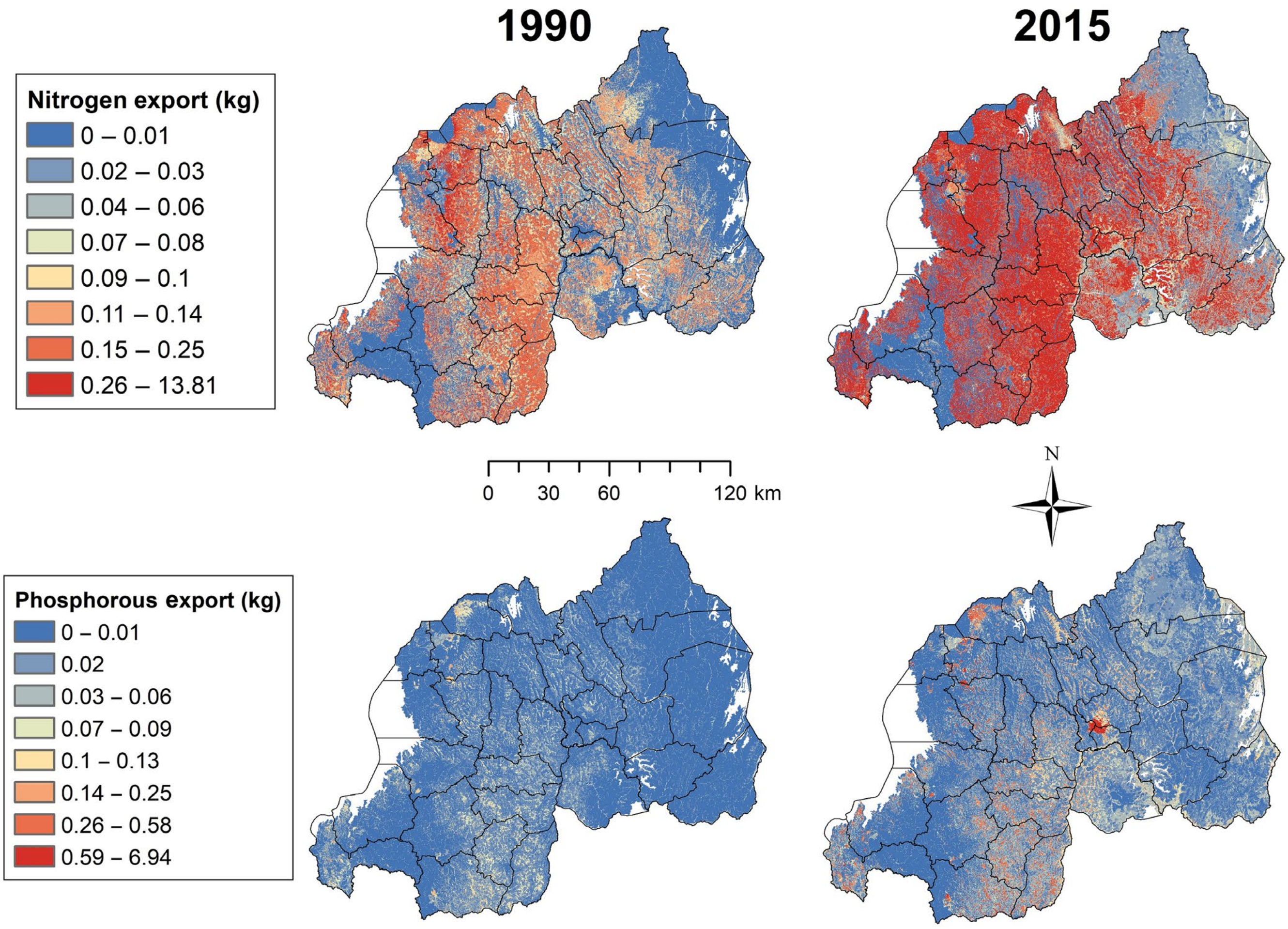


FIGURE 5 (Continued)

have less of their water delivered as quick flow – 23.7% across all parks in 2015, as compared to a national average of 41.8%. Relative changes in quick flow in the national parks were greatest for Nyugngwe NP (owing to increases in grassland and shrubland within the park from 2010 to 2015) and Gishwati-Mukura NP (primarily due to forest loss in the 1990s; Figure 7).

3.3 | Ecosystem service flows for irrigation, hydroelectric power and drinking water

Between 2010 and 2015, nation-wide sediment export increased by 38.9%, phosphorus exports increased by 10.6% and quick flow increased by 10.2%. By comparison, sediment export and quick flow in watersheds upstream of all hydroelectric dam sites increased modestly (+14.3% and +8.8%, respectively; Figure 8). For irrigation dam and water treatment plant sites, increases in sediment export were greater than the national average (+43.5% and +47%, respectively), as were increases in quick flow (+10.5% and +12.8%, respectively). Phosphorus exports upstream of water treatment plants increased by 20.2%.

Sites for 14 irrigation dams, 11 hydroelectric dams and 16 water treatment plants had upstream quick flow and sediment export increases above the national average (Figure 8). This represents 8.9% of Rwanda's hydroelectric generation capacity and 59.0% of its water treatment capacity. Sites for five irrigation dams, six hydroelectric dams and seven water treatment plants had upstream increases in 50% or more in both quick flow and sediment export. In all, 19 of Rwanda's water treatment plants had upstream phosphorus exports greater than the national average (representing 73.5% of the nation's water treatment capacity), 11 of which were greater than 50%. ES beneficiaries who depend on sites like these are likely at greater risk for the security of their water supplies, particularly under climate change.

4 | DISCUSSION

4.1 | Ecosystem service trends and implications

SEEA-EEA accounts can evaluate linkages between changes in land cover, multiple ES and their economic consequences (U.N. et al., 2014b). Ecosystem condition, potential supply and ES flows (Hein et al., 2016) degraded substantially in Rwanda from 1990 to 2015, particularly from 1990 to 2000 and 2010 to 2015. Deforestation

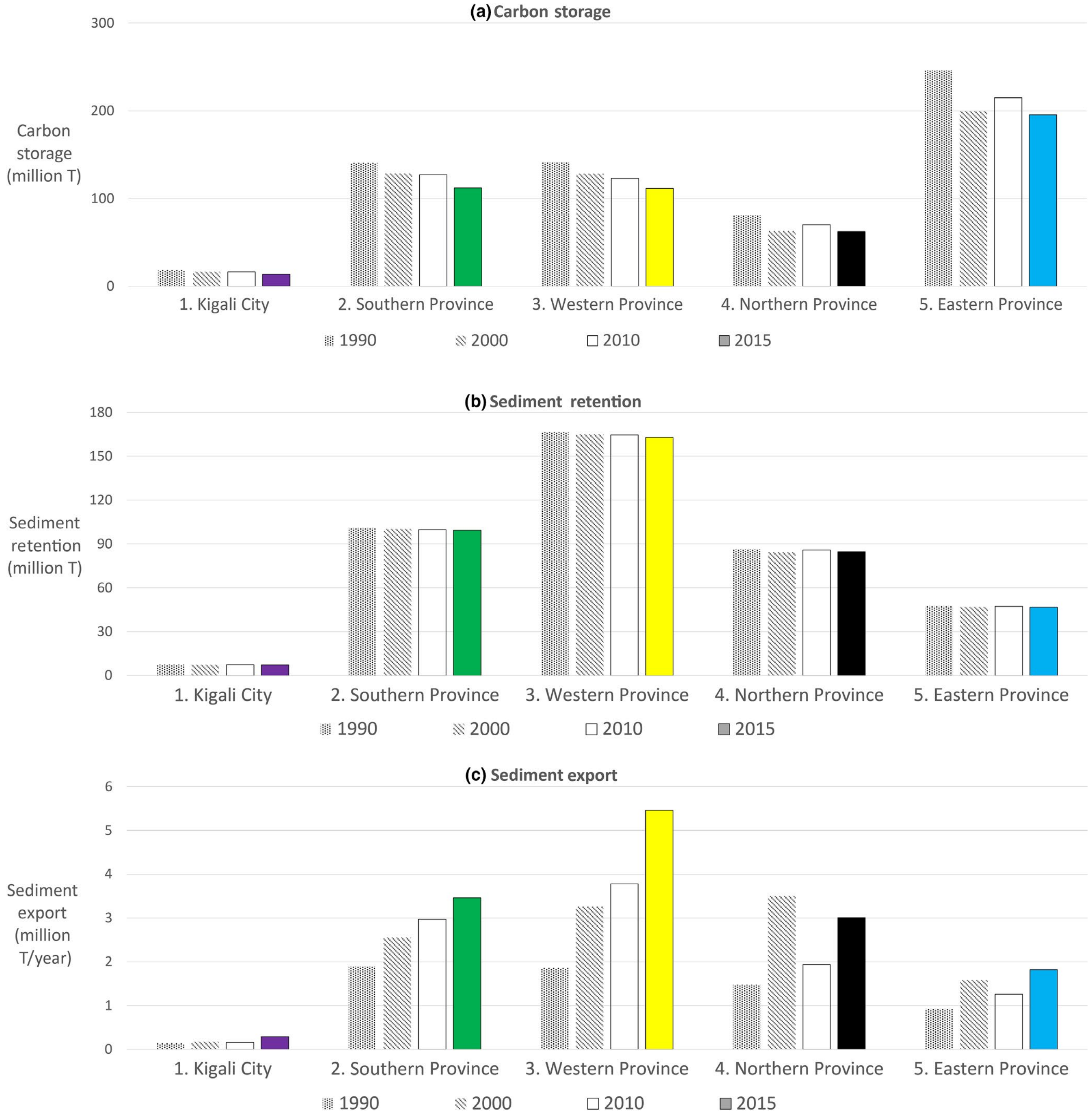


FIGURE 6 Changes in potential ecosystem service supply in Rwanda from 1990 to 2015, summarized by five provinces: (a) Carbon storage; (b) Sediment retention; (c) Sediment export; (d) Annual water yield; (e) Local recharge; (f) Quick flow; (g) Nitrogen export; (h) Phosphorus export

and environmental degradation during the conflicts of the 1990s are well documented (Ordway, 2015), and increasing deforestation since 2010 has been noted elsewhere (Hansen et al., 2013; Karamage et al., 2017; Kayiranga et al., 2016; Republic of Rwanda, 2018, though REMA 2015 report increasing forest cover, possibly of young trees not yet classified as forests in land-cover datasets developed from satellite imagery). Increases in nutrient exports, which were most pronounced from 2000 to 2010, can cause eutrophication of watercourses (Nahayo et al., 2016; REMA, 2015) and have undesirable impacts on water users within Rwanda and downstream nations. Particularly given Rwanda's ambitions to maintain and restore natural capital while pursuing economic development and poverty reduction and given the enactment of various laws to protect environmental quality over the last two decades, the 2010–2015 ES trends are problematic. In recognition that deforestation has increased since 2010, there is a need to better understand forest loss and its drivers and to track forest and land-cover change on a more frequent basis. Forest loss is likely at least partly due to

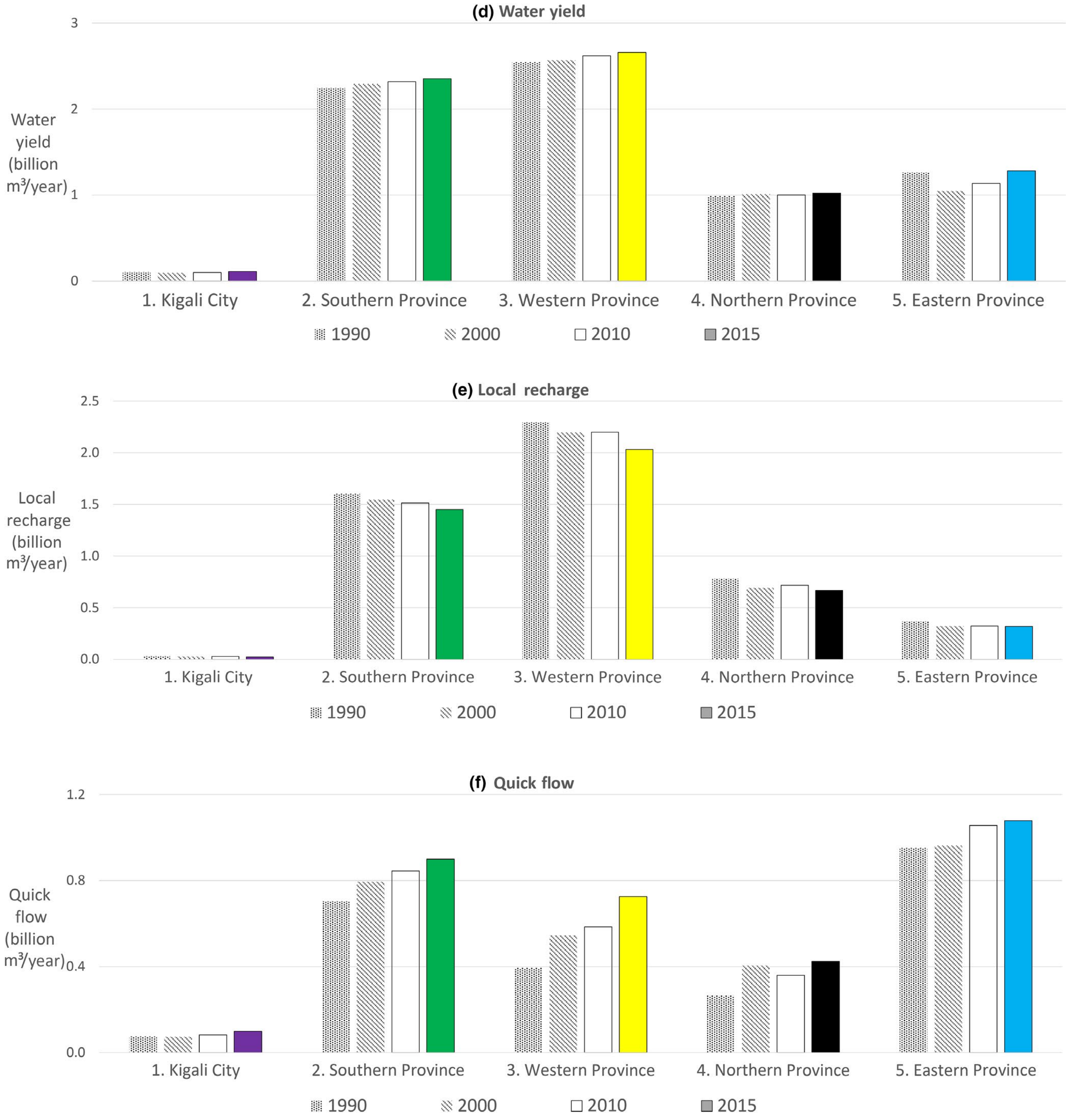
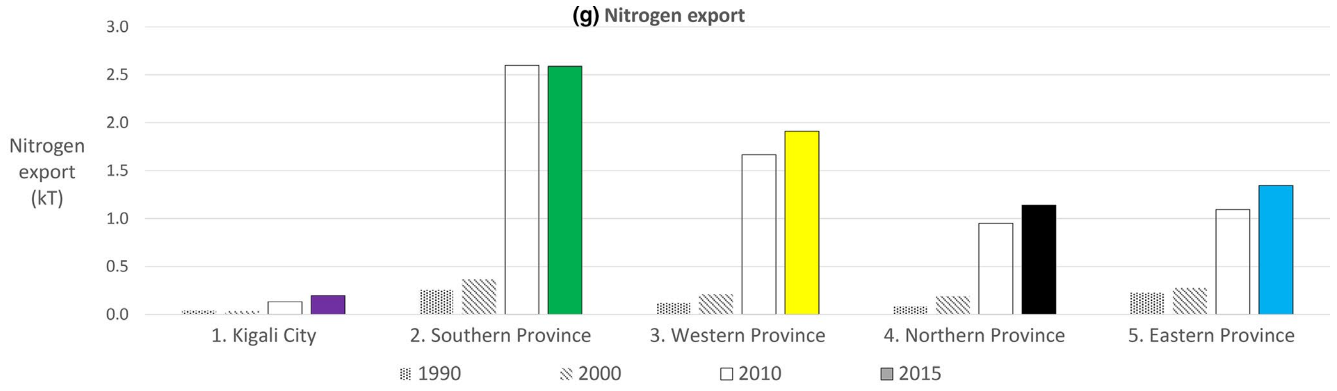


FIGURE 6 (Continued)

high population pressure in Rwanda, which makes conservation of natural habitats outside of protected areas challenging. These pressures stem from Rwanda's basic demographics as a small, landlocked nation with high population growth and the densest population in Africa.

Rwanda's ES trends reflect land-cover change over the 25-year study period. Carbon storage changes were driven by declines in land-cover types with greater carbon storage (forests, wetlands and shrublands) and expansion of areas with lower per-hectare carbon storage values (cropland, grassland and urban).[1] Increases in nutrient export were driven most strongly by increased fertilization of croplands from 2000 to 2010, and to a lesser extent by increases in cropland area from 1990 to 2000 and 2010 to 2015. Sediment export and retention changes were primarily driven by large-scale conversion of forested land to agriculture, and to a lesser degree changes in terracing of croplands. A small decline in annual water yield from 1990 to 2000 was driven by conversion of shrubland to cropland and grassland with greater assumed



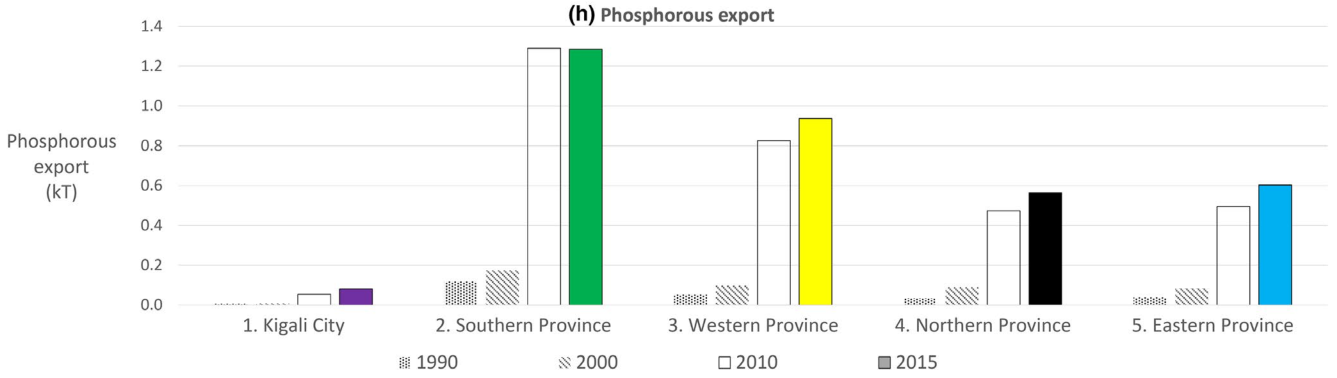


FIGURE 6 (Continued)

evapotranspiration. Declines in evapotranspiration from 2000 onward, which led to greater water yield, were driven by forest loss. Increases in quick flow and reductions in local recharge were most evident around Kigali City and districts with growing urban centres, which is likely due to increasing impervious surface cover. Other changes in quick flow and local recharge are attributable to not just the type and extent of land-cover change, but where it occurs (i.e. on soils with greater or lesser infiltration capacity, or further upstream or downstream).

Our results generally align with other ES studies in Rwanda. For instance, Karamage et al. (2017) found increasing runoff from 1990 to 2016. Soil erosion increases have previously been documented in Rwanda (Karamage, Shao, et al., 2016; Karamage, Zhang, et al., 2016), though calibrated models are still lacking. REMA (2015) notes localized problems with water quality and availability, particularly in the dry season. Our carbon storage estimate (495.3 MT nationally, 138.3 MT in forests, of which 58.5 MT was in above-ground and below-ground biomass) differed substantially from Rwanda's national forest inventory (DFS et al., 2016), which estimated above-ground and below-ground carbon to total 25.9 MT. Although well below our estimates, the national forest inventory includes carbon in plantations, shrubland and agroforestry areas only (i.e. it excludes forest carbon storage in protected areas, which we estimated at 79.5 MT); future work could better harmonize these results with ours. Our results are also generally comparable to those of Rukundo et al. (2018), who modelled multiple ES in Rwanda from 1990 to 2010 using InVEST. However, our study expands on theirs by (a) extending the analysis to 2015, (b) using a calibrated water model, (c) using the seasonal water yield model to quantify quick flow and local recharge, (d) using more up-to-date data, including Tier II land-cover data from RCMRD,[2] (e) accounting for changes over time in fertilizer application rates and the extent and effectiveness of terracing on soil erosion, and (f) modelling ES flows to water users and their changes over time.

Our results have important implications for water users – particularly for trade-offs that may emerge as the country plans to expand water use for irrigation, hydroelectric power, coffee washing and other uses (Republic of Rwanda & Ministry of Natural Resources, 2011), and between increased use of fertilizer to improve agricultural output and food self-sufficiency and in water quality and aquatic health. For instance, increases in fertilizer application have increased wheat and maize yields by factors of 2.5 to 3 (Republic of Rwanda, Ministry of Agriculture, & Animal Resources, 2013), but at the cost of substantially increased nutrient exports to the country's surface waters (Nahayo et al., 2016; REMA, 2015). Additionally, irrigated cropland was projected to grow from 18,000 to 100,000 ha from 2010 to 2017. Hydroelectric power expansion was planned from 69 MW of generation capacity in 2009 to 130 MW in 2012 (though problems with sediment impacts to hydroelectric power generation have previously been noted in Rwanda, Munyaneza, Majoro, Mutake, & Hagenimana, 2015). Domestic water users – particularly in rural areas – are targeted for expansion of reliable, safe and adequate drinking water. Coffee is Rwanda's fastest growing industry, with planned growth of coffee washing stations from 46 to 240 from 2005 to 2012 (Republic

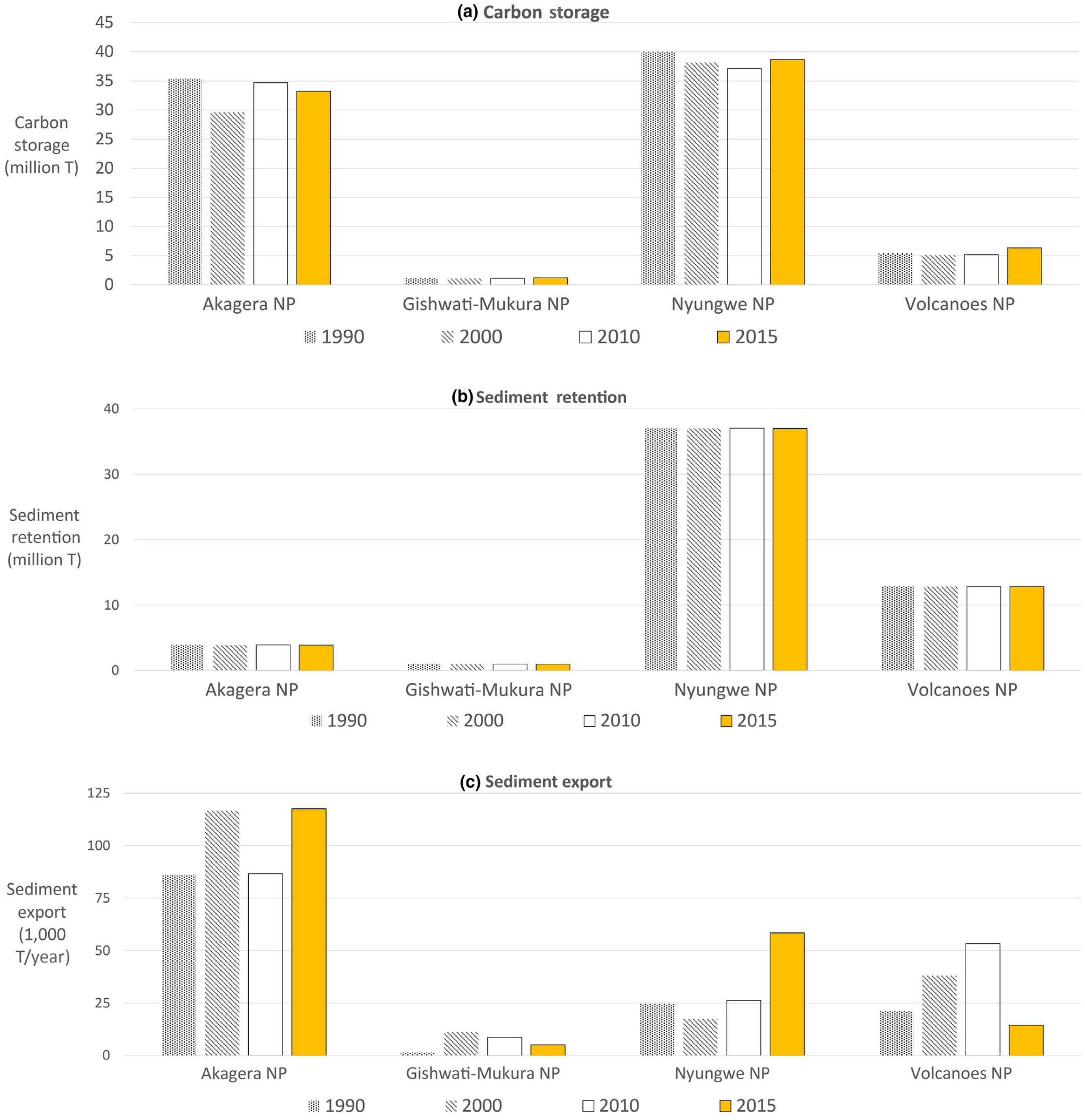
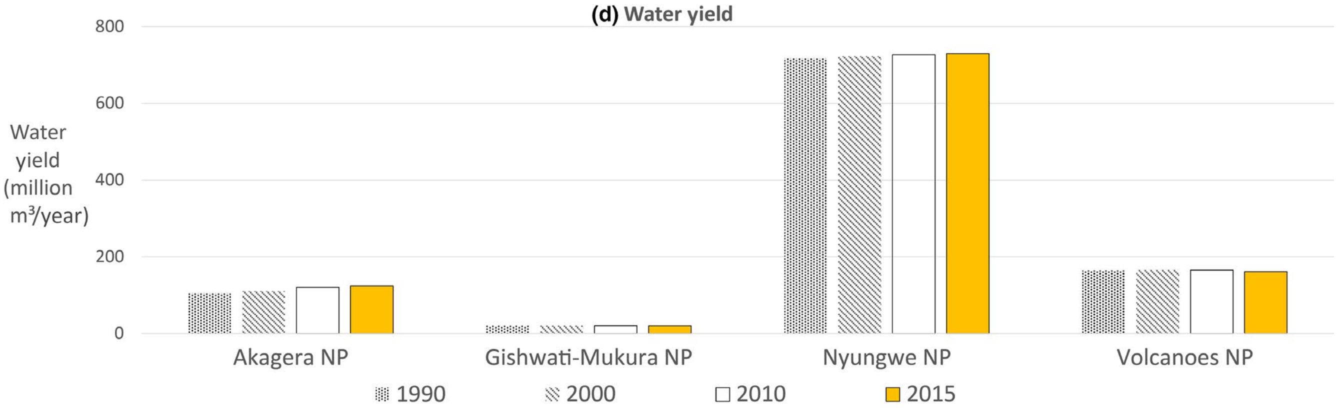


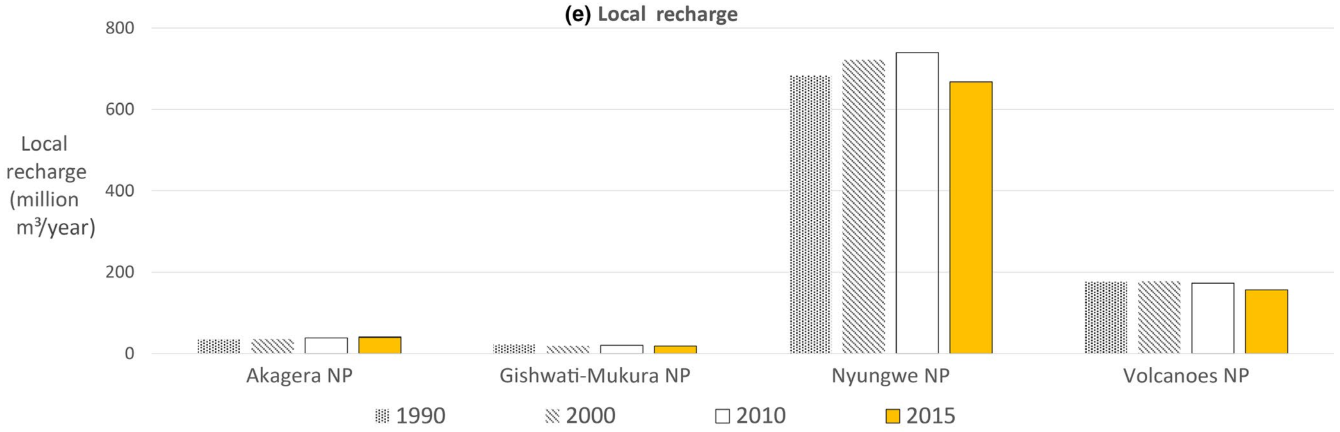
FIGURE 7 Changes in potential ecosystem service supply in Rwanda from 1990 to 2015, summarized by protected areas: (a) Carbon storage; (b) Sediment retention; (c) Sediment export; (d) Annual water yield; (e) Local recharge; (f) Quick flow; (g) Nitrogen export; (h) Phosphorus export

of Rwanda & Ministry of Natural Resources, 2011). Most coffee washing stations in Rwanda rely on water from springs and wells, making adequate groundwater recharge important for the future of this industry. While western Rwanda is relatively water-rich, the nation has problems with water quality and dry-season availability, which may be exacerbated by rising water demand, nutrient exports to aquatic systems, declines in local recharge and climate change. Our results augment information provided by Rwanda's water accounts (Republic of Rwanda, 2019), showing how land cover and water resources interact and how the country can better balance water use and natural resource protection.

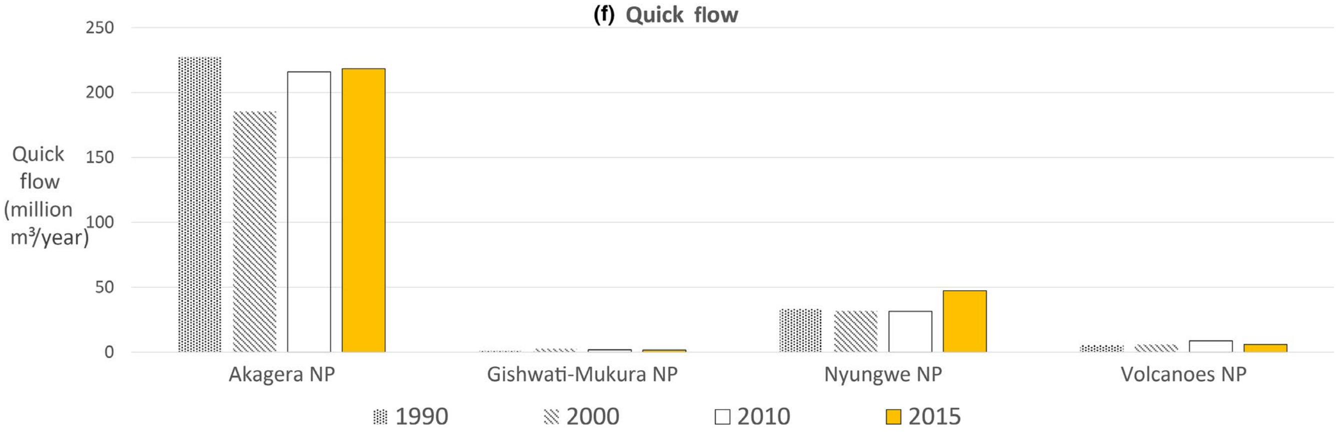
National parks cover 9% of Rwanda but are important for the protection and provision of ES. In 1990, the area now covered by four national parks provided 13.1% of the nation's carbon storage, 13.4% of its sediment retention and 18% of its local recharge (parks play a relatively minimal role in nutrient loading and export). As ES declined more rapidly outside of parks, parks' contribution to national ES rose – by 2015, providing 16% of its carbon storage, 13.7%



(d) Water yield



(e) Local recharge



(f) Quick flow

FIGURE 7 (Continued)

of its sediment retention and 19.6% of its local recharge. Particularly in the rainy and mountainous western part of the country, Rwanda's parks play key roles in protecting water quality, quantity and timing. Given Rwanda's role as a water supplier to downstream nations in the Congo and Nile Basins (many of which are water stressed), the protection of hydrologic ES by Rwanda's ecosystems is important for neighbouring nations as well. National park boundaries in Rwanda have changed over time, with Gishwati-Mukura NP created in 2015 but large parts of Akagera NP degazetted to accommodate refugees returning to Rwanda after the conflict of the 1990s (Apio, Plath, & Wronski, 2015). This shows how population pressures interact with conservation, which is critical to the maintenance of ES in Rwanda.

At least five potential solutions exist to the ES declines quantified in this study, all of which are being actively pursued by the Government of Rwanda and civil society. First, the importance of improved in situ soil and nutrient management, particularly through erosion control, has long been recognized (Ndabamenye et al., 2013) and is a focus of agricultural development efforts. In a sensitivity analysis of the effects of terracing on erosion, Rwanda would have needed to improve

FIGURE 7 (Continued)

its rate of terracing improvements from 2010 to 2015 by about 7.5 times to offset land cover change-induced soil erosion during that period. Improved outcomes for water quality may also be achievable by targeting reforestation to intercept nutrients and sediment before they flow into major waterways (Chaplin-Kramer et al., 2016). Second, the government is actively promoting renewable energy, particularly hydroelectric generation and methane extraction from Lake Kivu, to reduce pressure on forests for biomass energy. Third, payments for ecosystem services (PES) have been discussed as a means of incentivizing smallholder farmers in Rwanda to adopt sustainable agriculture management practices to protect soil and water resources (Tetra Tech & LTS Africa, 2018). Fourth, by developing 'green cities', Rwanda aims to densify its urban cores, reducing population pressure on non-urban areas (REMA, 2017; World Bank & Government of Rwanda, 2019). Finally, the creation of the Rwanda Water and Forestry Authority in early 2017 from the former RNRA explicitly recognizes the linkages between forests and water, and the need to jointly manage these critical resources. Our ecosystem accounts and their underlying models can assist in tracking the effectiveness of these strategies (e.g. soil erosion control), spatial targeting of PES (i.e. to small watersheds upstream of water users, with high risk of land-cover change, low opportunity costs for conservation, and monitoring infrastructure to detect change, building on Figure 8), and quantifying linkages and dependencies between natural resources (e.g. forests and water).

4.2 | Caveats

In this paper, we modelled ES in Rwanda using the latest data, a calibrated annual water yield model, terracing data to inform a soil erosion model (Supporting Information Appendices A–C), and applied a seasonal water yield model to better quantify hydrologic ES. Relative to past ES modelling efforts in Africa that rely on older, coarser resolution, or global data or lack calibration (Gourevitch et al., 2016; Leh, Matlock, Cummings, & Nalley, 2013; Rukundo et al., 2018), results of this study are relatively robust. Still, several important caveats apply.

First, sediment and nutrient load data needed to calibrate soil erosion and nutrient models are scarce in Rwanda (Muvundja et al., 2009; Uwimana, Dam, Gettel, & Irvine, 2018); an attempted calibration using sediment load data for watersheds draining into Lake Kivu (Muvundja et al., 2009) had relatively low predictive power. A national water-quality monitoring programme with adequate spatio-temporal coverage and co-located with stream gages could provide data to calibrate sediment and nutrient models. New water-quality monitoring efforts begun in 2017 by the Ministry of Natural Resources may aid in future model calibration efforts (Christian & Vedaste, 2017).

Second, our analysis of dams and water treatment plants required delineation of their upstream watersheds. We confirmed the

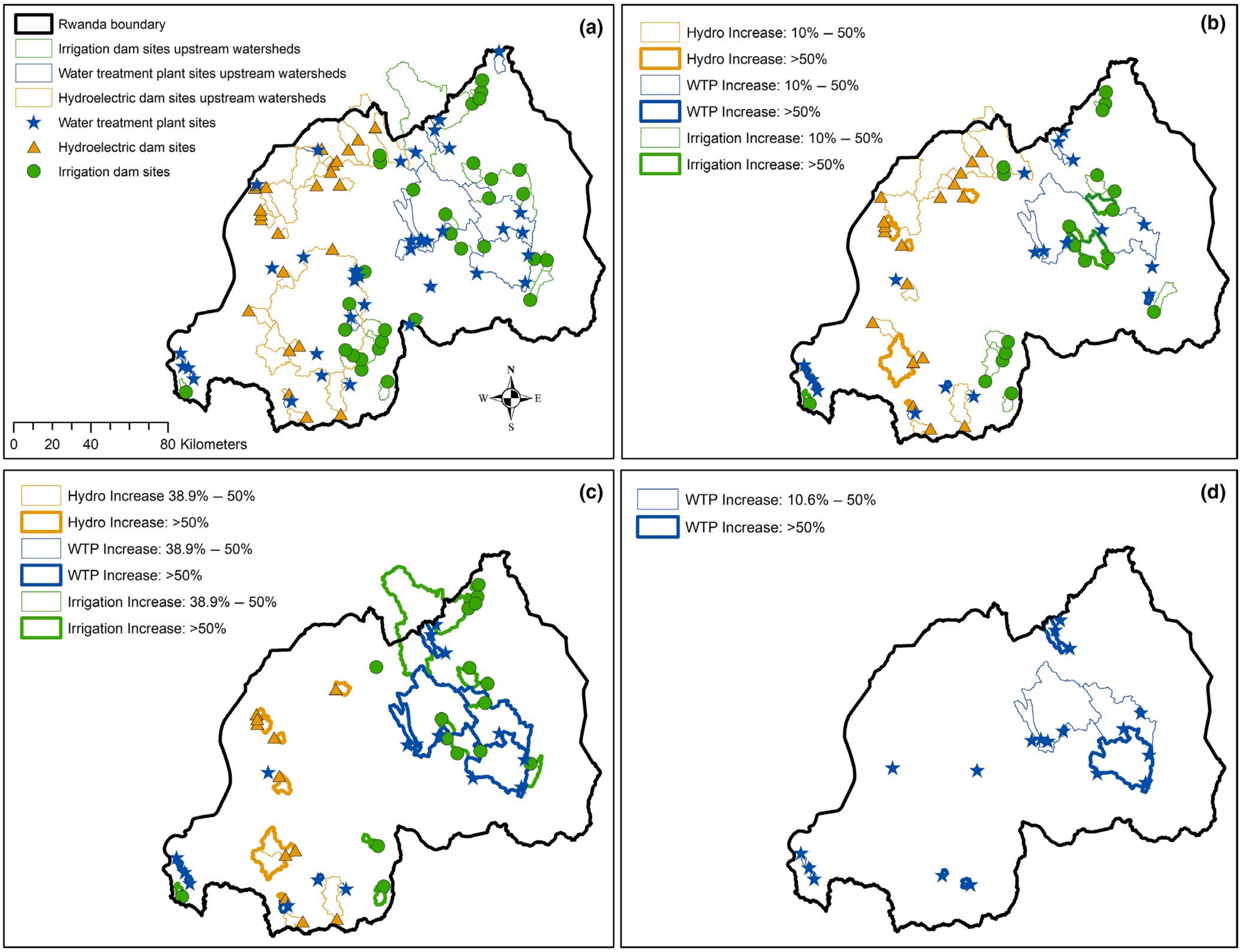


FIGURE 8 (a) Upstream watersheds of all hydroelectric dam, irrigation dam and water treatment plants in Rwanda. (b) Watersheds with greatest quick flow increases, 2010–2015. (c) Watersheds with greatest sediment export increases, 2010–2015. (d) Watersheds upstream of water treatment plants with greatest phosphorus export increases, 2010–2015

locations of some existing facilities using satellite imagery. However, watershed delineation requires that facilities be accurately located on river flow accumulation lines, and in some cases, the facility location was ambiguous, introducing uncertainty into our analysis. We suggest a full review of facility locations with Rwandan utility or agency staff to confirm exact water-use locations prior to the use of this information in precise spatial natural resource planning. Additionally, the use of the national average and 50% increases in sediment export and quick flow (Figure 8) are admittedly arbitrary cut-offs to illustrate the use of ES flow information in planning. Dam or water treatment plant managers could better inform the development of more rigorous sedimentation or quick flow thresholds for integrated land and water resources planning.

Third, data limitations prevent our current approach from being able to answer management questions about ES trade-offs related to plantations, including *Eucalyptus* and important perennial crops like tea, coffee and bananas. Although *Eucalyptus* is an extremely common planting in Rwanda and perennial crops are of high economic importance, current land-cover data do not distinguish between natural and planted trees, nor do we have field data specific to individual species that would enable analysis of such ES trade-offs.

Fourth, where possible, we used national datasets, which are typically more trusted and often of better quality than global datasets. In some cases, however, national data were dated and/or incomplete (e.g. the national soil survey dates to the late 1980s with limited sampling inside national parks, Verdoodt & van Ranst, 2006). As more national data become available, they should further improve the quality and credibility of our results. For example, the development of a public, national-scale water data portal should enable improved calibration of hydrologic ES models in the future as more data become available (Rwanda Water & Forestry Authority, 2019).

Finally, given data limitations and unresolved conceptual issues (e.g. the fact that sediment retention is a non-rival service simultaneously benefitting multiple water users in the same watershed), it was not possible to construct a physical use table. This conceptual issue is one of many being addressed by the SEEA-EEA revision process

(U.N., 2018), which should enable the inclusion of physical use tables in future Rwandan ecosystem accounts.

4.3 | Next steps for ecosystem accounting in Rwanda

We quantified ES in Rwanda for four intervals over a 25-year period. While adequate to show long-term trends, 5- to 10-year intervals are suboptimal for integration with more regularly produced national economic accounts, particularly given Rwanda's demand for official statistics in decision-making (Stage & Uwera, 2018). Land-cover data – a key input to many ES models – are now increasingly being produced with greater temporal resolution. Examples include the European Space Agency's Climate Change Initiative (ESA-CCI, 2017) and RCMRD's use of TimeSync software to begin production of high-resolution annual land-cover change maps for African nations using cloud computing (Cohen, Yang, & Kennedy, 2010; SERVIR Global, 2017). These offer the possibility that ecosystem accounting can become part of a regularly updated monitoring programme with greater relevance for decision-making, rather than an occasional exercise. Particularly in nations or regions with high population pressure and the potential for rapid land-cover change, regular updates to ecosystem accounts are important to avoid mistaken assumptions that land cover and ES trends are stable (as was the case in Rwanda from 2000 to 2010, but not 2010 to 2015). Bagstad, Cohen, Ancona, McNulty, and Sun (2018) provide further guidance on the sensitivity of ES results to data and model selection, which will be relevant when national land-cover data cannot be generated annually and the use of global or regional datasets is considered.

Future analyses could consider additional ES that matter to the country. For instance, flood regulation is an important ES in Rwanda, but beyond the use of simple proxies (Martinez-López et al., 2019) requires more complex models and underlying data than are currently available. Future ecosystem accounts could also address provisioning and cultural ecosystem services, for instance, tourism (Banerjee et al., 2018) and fuel, timber and food (NISR, 2018b). Inclusion of more ecosystem services, including provisioning and cultural services, would more fully quantify ecosystems’ contribution to Rwanda's economy.

InVEST provided a suitable platform for biophysical modelling of potential ES supply (Hein et al., 2016), and is one of several modelling tools available for ecosystem accounting (Bagstad, Semmens, Waage, & Winthrop, 2013). Although feasible to apply in Rwanda, the burden of InVEST model development, parameterization and calibration remains high for national governments in developing nations in the absence of external technical assistance. Further work to more efficiently reuse ES data and models and otherwise lower the barriers and time requirements for ES modelling is thus needed for more widespread application of ecosystem accounting in developing nations. To quantify ES flows rather than just potential supply, we used a GIS watershed delineation tool to understand how water quality, quantity and timing changes affect different industries. Similar GIS algorithms can be used to quantify other types of ES flows, providing more complete inputs to ecosystem accounts (Bagstad, Johnson, Voigt, & Villa, 2013).

5 | CONCLUSIONS

In this paper, we provide an initial view of ecosystem condition and physical ES supply trends for Rwanda that can serve as a foundation for more complete ecosystem accounts, including analysis of additional ES and monetary accounts (U.N. et al., 2014b). Economic valuation to develop monetary supply-use tables is a next step and will require greater integration with both Rwanda's water and national economic accounts. Although simple valuation is currently possible using, for example, the social cost of carbon and water productivity data from the water accounts (Republic of Rwanda, 2019), more sophisticated but data-intensive approaches to value ES like sediment regulation would be more informative for decision-making. This could incorporate additional key industries such as mining and coffee and tea production.

Ecosystem accounts are useful for helping to frame trends already uncovered in Rwanda's land and water accounts (Republic of Rwanda, 2018, 2019), and for understanding the effectiveness of past economic development policies such as EDPRS and Vision 2020 (Republic of Rwanda, 2000, 2013). In Rwanda's case, the stabilization of ES losses in the 2000s appeared to indicate success in balancing economic development, poverty reduction and environmental protection. However, ES gains have reversed since 2010, showing the challenge of sustaining natural capital in the face of rapid economic and population growth (e.g. Marques et al., 2019). As the Government of Rwanda contemplates ambitious future policies such as the upcoming National Strategy for Transformation I (the successor to EDPRS) and Vision 2050, ecosystem accounts can help track progress, quantify trade-offs, and set realistic baselines from which to develop comprehensive and linked environmental-economic policies. Furthermore, ecosystem accounts can illustrate linked trends and previously unidentified trade-offs in the environment, economy and human well-being of other rapidly changing African nations.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

K.J.B., J.C.I., G.-M.L., M.M., M.B., S.P., D.R. and C.U. designed the research. K.J.B., Z.H.A., D.K., B.M. and N.L.N. performed the research. K.J.B., Z.H.A., M.B., D.K., M.B., E.R., E.R. and N.L.N. contributed data, ran models and analysed data. K.J.B., J.C.I., G.-M.L. and M.M. wrote the paper. All authors approved the final version of this paper.

DATA AVAILABILITY STATEMENT

A data release containing all relevant datasets will be available within the US Geological Survey Science Data Catalog https://data.usgs.gov/datacatalog/; https://doi.org/10.5066/F72806JN (Bagstad et al., 2019).

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ENDNOTES

[1] Land-cover data generally showed declines in forest density (Figure 2), with the exception of recovery of dense forests in protected areas from 2010 to 2015. Dense forests are classified as having >70% tree canopy cover, moderate forests from 40% to 70% cover and sparse forests as 10%–40% cover. Transitions between forest cover classes indicate the crossing of these thresholds, but do not tell us how far a given cell is from that threshold. It is thus possible that some changes in forest density could reflect cells with forest cover near a threshold that crossed it from one time period to the next.

[2] RCMRD has produced two land-cover data products for Rwanda – Level I with 6 land-cover classes and Level II with 13 classes. Like any land-cover data, classification error rates will be lower for datasets with fewer land-cover classes. For the 1990–2010 data, Level II accuracy was 80.0% and Level I accuracy was 86.4% (RCMRD-SERVIR Africa, 2013). For 2015, Level II had 77.5% accuracy and Level I 79.6% (RCMRD, 2017) – so relatively little accuracy was lost in moving from 6 to 13 land-cover classes. While the 2015 maps were produced as part of a separate effort than the 1990, 2000 and 2010 maps, the developers of the 2015 data used similar methods and performed accuracy assessments and comparisons with the earlier data to ensure its compatibility. Rukundo et al.'s (2018) trends for ES modeled based on Level I land-cover data for 1990 to 2010 were quite similar to ours, which gives us further confidence that ES trends are robust to the choice of the chosen thematic resolution for land-cover maps. We lacked the data to uniquely parameterize open versus closed grasslands and shrublands in the carbon, RUSLE C factor (SDR model), and Kc and root depth (annual water yield model) lookup tables, and different forest, grassland/shrubland, and cropland types in the NDR model lookup table (Supporting Information Appendix A). In these cases, a more detailed land-cover classification does not help us to make a more refined assessment, but further ecological studies could help to better distinguish between ES provision differences when using Level II land cover in future ecosystem accounts.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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