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Key Points:
- Food, energy, and water (FEW) resources, provisioning services, and health outcomes are interrelated
- Data-driven techniques can elucidate FEW interrelationships
- Socioeconomic and governance factors strongly influence FEW security in sub-Saharan Africa

Supporting Information:
- Supporting Information S1
- Table S4
- Table S5

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Prominent Influence of Socioeconomic and Governance Factors on the Food-Energy-Water Nexus in sub-Saharan Africa

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Abstract Food, energy, and water (FEW) are primary resources required for human populations and ecosystems. Availability of the raw resources is essential, but equally important are the services that deliver resources to human populations, such as adequate access to safe drinking water, electricity, and sufficient food. Any failures in either resource availability or FEW resources-related services will have an impact on human health. The ability of countries to intervene and overcome the challenges in the FEW domain depends on governance, education, and economic capacities. We distinguish between FEW resources, FEW services, and FEW health outcomes to develop an analysis framework for evaluating interrelationships among these critical resources. The framework is applied using a data-driven approach for sub-Saharan African countries, a region with notable FEW insecurity challenges. The data-driven approach using a cross-validated stepwise regression analysis indicates that limited governance and socioeconomic capacity in sub-Saharan African countries, rather than lack of the primary resources, more significantly impact access to FEW services and associated health outcomes. The proposed framework helps develop a cohesive approach for evaluating FEW metrics and could be applied to other regions of the world to continue improving our understanding of the FEW nexus.

1. Introduction

Food, energy, and water (FEW) resources are critical for the development and survival of societies. However, access to these resources is limited in many parts of the world; currently, billions of people are facing FEW insecurity (United Nations, 2018b). The path to global FEW security is further complicated by challenges such as population growth, climate change (including extreme weather events), and environmental degradation by anthropogenic activities (Biggs et al., 2015).

Researchers have studied the security of the individual resources of FEW for decades, highlighting different metrics or indices of interest for the individual security of resources. Metrics and measurements have generally increased in complexity over time in conjunction with our increased understanding of resource security factors. For example, in the water security domain, indices evolved from the Falkenmark Index (which is a simple measure of physical water resources availability in a country) to consider household, economic, urban, environmental, disaster resilience, and governance aspects (Asian Development Bank, 2016). Similarly, in the energy security domain, approaches evolved from measuring the availability of fossil and other types of energy resources (i.e., energy reserves) to considering diversity of energy resources, import dependence, infrastructure development, societal effects, environmental impact, efficiency, and economic and political factors as important components of energy security (Ang et al., 2015; APERC, 2007). Food security measures also consider social and political aspects such as accessibility and utilization in addition to physical factors (International Food Policy Research Institute, 2015). Health outcomes such as diarrhea and malnutrition are also typically included in the individual resource security metrics. However, individual metrics do not show the interactions and dynamics among the components, which is important because the security of each resource is often connected to the other resources (e.g., drinking water access impacts utilization aspects of food security, cooking of food relies on energy resources, and water resources are used to generate electricity). Solely addressing or emphasizing scarcity and insecurity issues of any one of the three resources could overlook opportunities for improvement in the other two sectors and fail to capture the synergies (Al-Saidi, 2017).

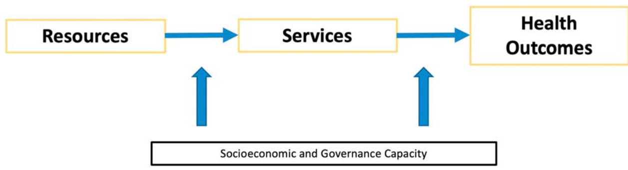

Figure 1. Conceptual food, energy, and water-resources-services-health framework distinguishes between three domains: (1) resource availability, (2) accessibility to services, and (3) food, energy, and water-related health outcomes for the three sectors: food, energy, and water. The relationships among these three domains are influenced by both direct sectoral and cross-sectoral linkages as well as socioeconomic and governance capacities of regions.

Although there is a consensus on the need for managing FEW resources as a FEW nexus, methods for doing so are relatively underdeveloped (Biggs et al., 2015; Mcgrane et al., 2018; Perrone & Hornberger, 2014). Statistical and data analysis techniques used to quantify some interrelationships of the FEW nexus have generally applied "black box" approaches (Ozturk, 2017; Zaman et al., 2017) and often did not include critical components such as social-economic factors leading to incomplete evaluation of nexus interactions (Albrecht et al., 2018). For example, Sušnik, (2015, 2018) used global data to regress the countries′ gross domestic product (GDP) against total/sectoral water withdrawals, total/specific crop production, and electricity consumption/generation, finding strong correlations between GDP per capita and all three resources metrics. Willis et al. (2016) focused on measures of availability and accessibility of FEW resources to produce subindices for each resource that were then aggregated to a FEW index for countries globally. Both of these approaches overlooked governance factors, and the resources were siloed such that cross-sectoral influences (e.g., influence of water withdrawals and crop production on electricity consumed) were not considered. Other work has used a variety of techniques to explore parts of the FEW nexus such as global virtual water networks and life cycle analyses (e.g., Feng et al., 2014; Konar et al., 2011; Yuan et al., 2018) but have not stressed relationships with governance. Consistent inclusion of governance will be especially important given the potential for and consequences of the conflicts generated by scarcity of resources (Märker et al., 2018).

There is a need to develop a cohesive framework to elucidate key linkages and guide the analyses. Toward this need, we introduce a FEW analytical framework that leverages the theoretical understanding of resource systems to better elucidate nexus interactions (Rasul & Sharma, 2016). Specifically, the framework distinguishes between three domains: resources availability, access to FEW-related services, and FEW-related health outcomes (Figure 1). This FEW resources-services-health (RSH) framework clarifies the complex causal mechanisms between the domains, notably that the conversion of raw resources (e.g., water, arable land, and minerals) into critical services (e.g., drinking water, food, and energy) is needed in order to have an impact on FEW-related health outcomes (e.g., diarrhea, undernourishment, and deaths attributed to air pollution; Dora et al., 2015; WHO, 2018b). Cross-sectoral influences can occur during both the conversion of resources to services (e.g., use of water for energy and use of energy for water) and between the services and health domains (e.g., inadequate provision of water services not only impacts diarrhea rates but also influences nutrient uptake and thus food-related health outcomes such as malnutrition; Dora et al., 2015; Hunter et al., 2010). In addition to physical variables, the dynamics between the domains are mediated by important socioeconomic and governance (SG) capacity variables such as education, political stability, and infrastructure availability; SG variables can influence nexus interactions between resources and service domains as well as between the services and health domains (Figure 1). The FEW-RSH framework provides a comprehensive lens for analyzing and comparing the dynamics and nuances of the FEW nexus that can be applied to regions at any scale. The inclusion of SG in the framework constructs the bridges across disciplinary silos and emphasizes the importance of the human aspect in the FEW nexus.

This study implemented the FEW-RSH framework to understand nexus interrelationships in 38 sub-Saharan African (SSA) countries (Figure 2), a region facing significant resource insecurity (United Nations, 2018a); the Democratic Republic of the Congo was not included in the analyses due to a lack of data. The framework is implemented using a data-driven cross-validated stepwise regression technique to evaluate primary drivers of the service and health outcomes.

2. Methods

The data analysis consisted of collecting, categorizing, processing, and regression analysis of FEW-related data (Figure 3). A cross-validated stepwise regression analysis (CVSRA) method, which systematically evaluates the pool of candidate metrics for each linkage by considering the cross-validation errors of the findings, was implemented to examine and elucidate both sectoral and cross-sectoral linkages (Figure 4 and Table 2). Metrics with the smallest cross-validation errors were selected for each linkage or interlinkage exploration. Analysis was conducted for each of the FEW-services as well as the FEW-health outcomes as dependent

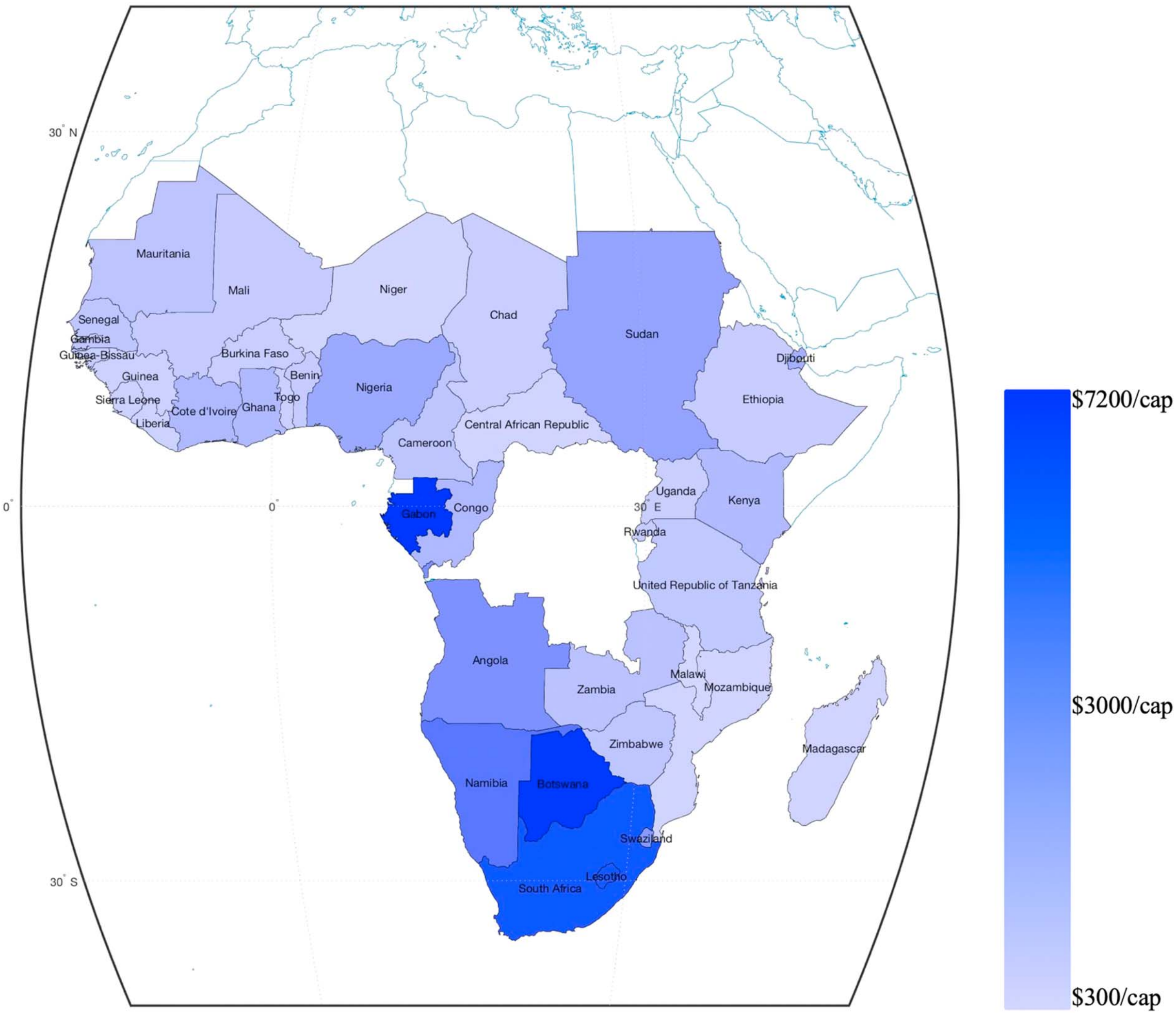

Figure 2. The 38 sub-Saharan countries analyzed in this study, with the color gradient indicating gross domestic product per capita in $US of each region.

variables. Direct sectoral linkages, cross-sectoral linkages between two sectors, and FEW nexus linkages across all three sectors were considered.

1. Data collection. All available national-level data were collected from multiple sources (e.g., the United Nations and World Bank; Figures 2 and 5 and supporting information Table S1). Metrics that capture human capacity measures that influence the processes between the domains were also included in the data set (Table S2). For each of the metrics listed in Tables S1 and S2, the most recent data (as of 31 December 2017) were collected to most effectively represent the current FEW-related information and conditions of those countries; we assume that the values did not vary significantly between years. Some of the metrics captured temporal variability of resources, services, or health outcomes (e.g., interannual and seasonal variability of water resources as well as food production and supply variability). Therefore, the data assembled for this analysis generally have a zero time dimension, while the spatial resolution is at the country level. More data were available for the water sector (38 countries) than energy sector (20) or food (21) sector (Figure 5). Overall, 13 countries had the full set of FEW data analyzed in this research.
2. Data categorization. The collected metrics were first categorized into the three sectors (water, food, and energy) and domains following the FEW RSH framework (Figure 1). The metrics were further categorized into the respective domains: resources, services, and health, which represent the availability of the FEW resources, human accessibility to the processed FEW resources, and health of the people, respectively (Figure 6). Socioeconomic and governance capacity variables were similarly categorized into general as well as sector-specific variables (Table S2).

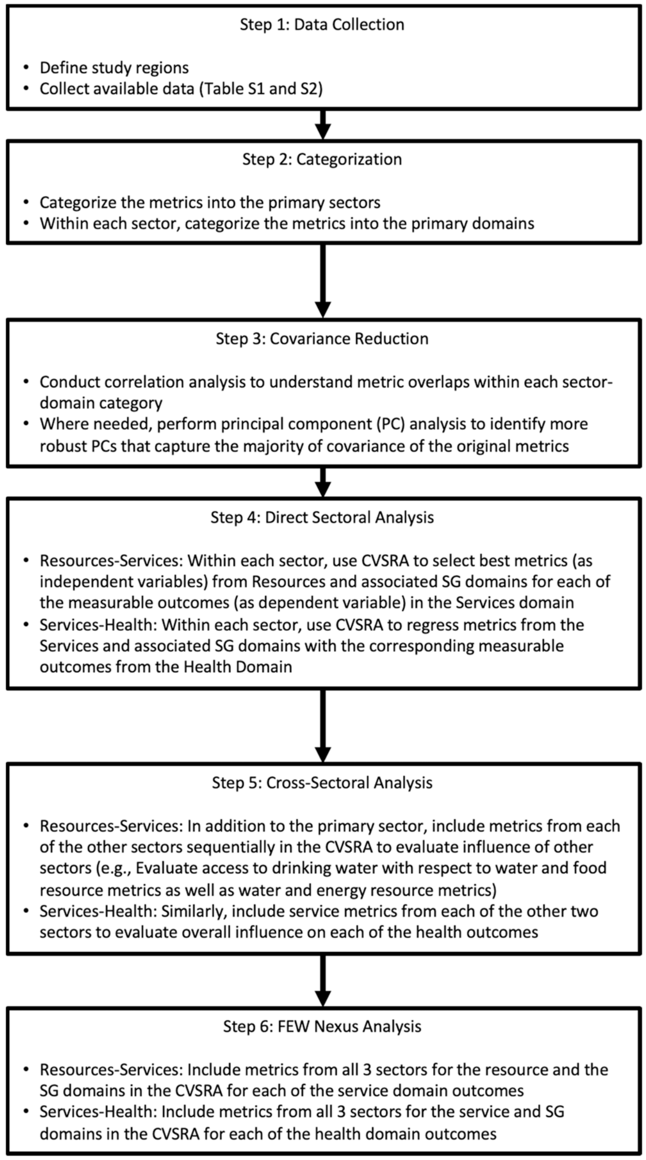

Figure 3. Overview of the data analysis methodology. CVSRA = cross-validated stepwise regression analysis; SG = Socioeconomic and Governance Capacity.

3. Covariance reduction. Within some of the categories, there were multiple metrics containing overlapping information or explaining similar phenomenon (e.g., the six World Bank Governance indicators are calculated from different combinations of the same underlying variables; World Bank, 2018b). We used correlation analysis to first identify highly correlated variables (e.g., the Pearson Correlation Coefficient of Flood occurrence and Total renewable water resources in the water resources domain is −0.76; Table S5). To reduce double-counting and collinearity issues, principal component analysis (PCA) was used to derive independent principal components (PCs) that capture the majority of the variance in the raw metrics. In the regression analysis, fewer PCs were selected than the number of raw metrics, which reduced the dimensionality and improved the robustness of the model performance (Çamdevýren et al., 2005; James et al., 2013). Other metrics were combined (either by summing or differencing) to reduce redundancy (Table S3). These processed variables are referred to as "derived metrics" for clarity. Some of the data with skewed distribution were log10 transformed prior to further analyses (Tables S3 and 2).
4. Regression analyses. Relationships between the resources and services domains as well as services and health domains were evaluated using a regression approach. Regression analyses were first implemented to identify important metrics with each sector (i.e., direct-sectoral linkages). The analysis was then

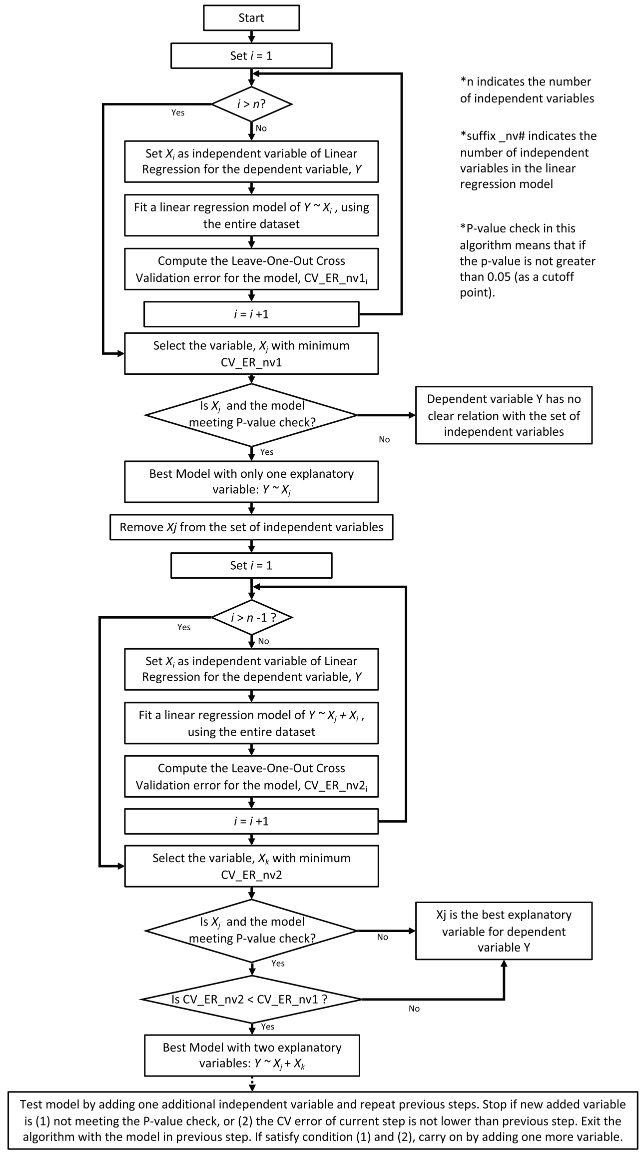

Figure 4. Flow chart of the cross-validated stepwise regression analysis, where i is the index of variables inside one running cycle of the algorithm, j is the index of the first selected significant variable, k is the index of the second selected significant variable, and so on. *CV_ER_nv#* means the cross-validation error of independent variable i for the linear regression model with # numbers of independent variables.

repeated to evaluate interactions between the primary sector and one of the remaining sectors (i.e., cross-sectoral linkages). Finally, analyses were implemented to evaluate linkages among all three sectors (i.e., FEW nexus).

Stepwise selection methods are a common and widely used tool to select the best subset of predictors for models when there are many predictors for selection. In the traditional stepwise regression approach, the variable to select or remove in forward or backward method at a certain level (e.g., model with n variables named as the nth level) is based on F-to-enter or F-to-remove values ($F = t$ value^2). This approach, however, has been criticized for its selection bias, which can lead to inconsistencies in the final model (Whittingham et al., 2006).

To overcome the issues of the traditional stepwise regression method, researchers have used the Information-Theoretic model selection such as Akaike Information Criterion (AIC) to penalize models with a high number of variables to prevent overfitting (Whittingham et al., 2006). We chose to use Leave-One-Out

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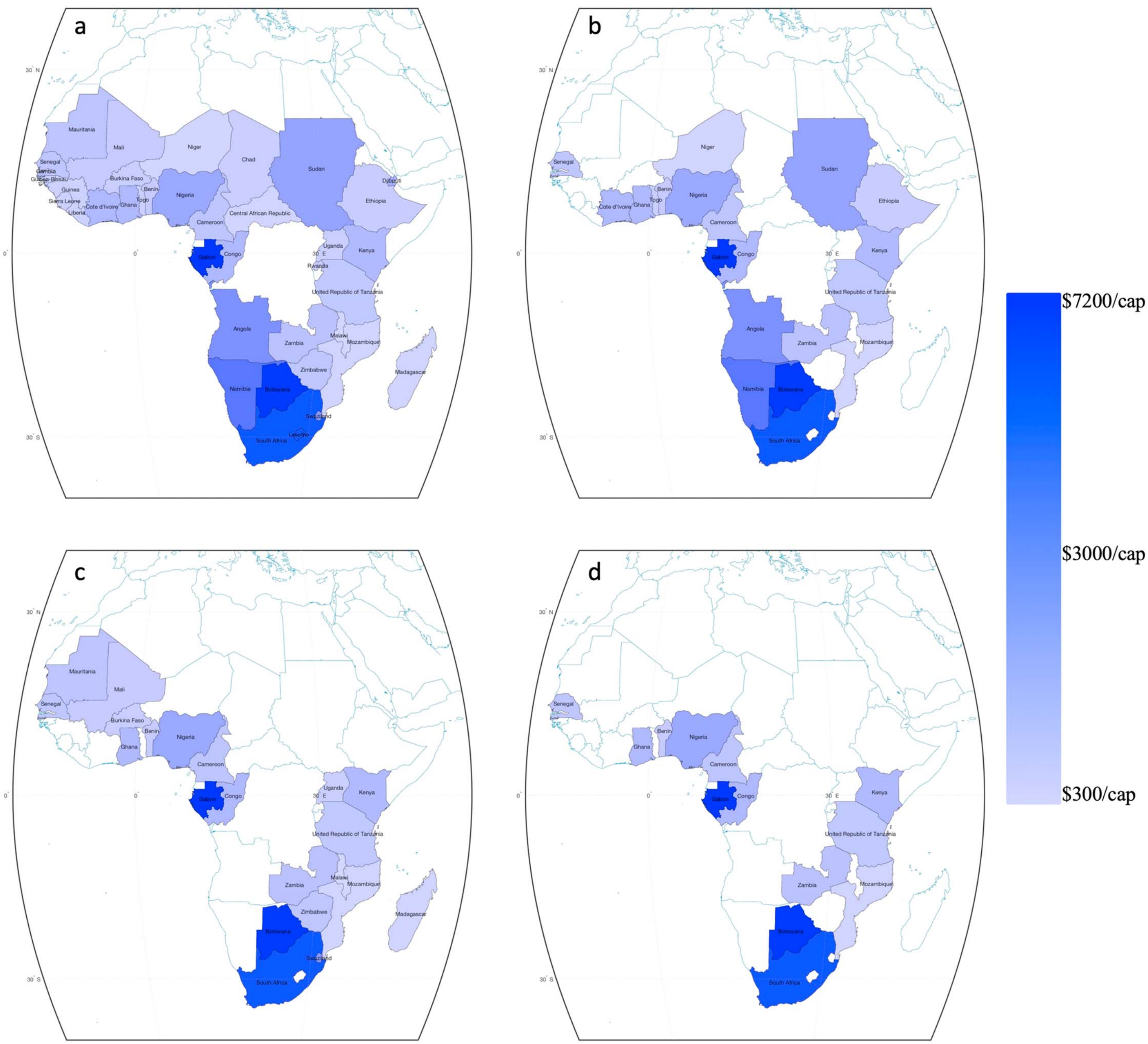

Figure 5. Countries with available data for the regression analyses. Direct linkage analyses were conducted for (a) water sector (n = 38), (b) energy sector (n = 20), and (c) food sector (n = 21). Cross-sectoral analyses considered the joint set of countries for each of the direct linkage analyses. Food, energy, and water nexus analysis was conducted for (d; n = 13). The colors indicate each country's gross domestic product per capita.

Cross Validation (LOOCV) error as the criterion of variable selection. While LOOCV and AIC are asymptotically equivalent (Stone, 1977), LOOCV can explicitly test the prediction error on all data points while systematically removing one variable (in our case, all associated values of a country) from the full data set. The LOOCV is suitable in cases such as ours because there are some high leverage points, and we do not have a large data set. The CVSRA returns the set of independent variables with the minimum LOOCV error (Figure 4). The AIC results are generally consistent with the LOOCV results (Table S4). In three of 32 models, there was a difference in one of the variables selected but in these three instances the chosen metrics for both LOOCV and AIC were from the same category so the difference would not affect our interpretation of the results. While in some cases (Table S4), adding an additional variable can achieve marginally lower

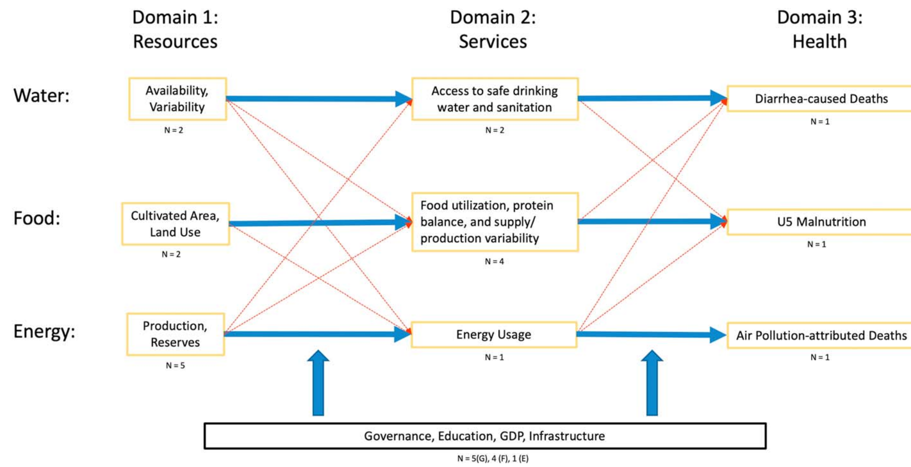

Figure 6. Categorization of the metrics used in the regression analyses by sector and domain. The "N"s refer to the total number of metrics within each category. The solid blue arrows indicate focus of analysis for direct sectoral linkages, while the dashed red arrows indicate analyses conducted for cross-sectoral and food, energy, and water nexus CVSRAs.

LOOCV error, we chose to limit the number of variables allowed to no more than three to control overfitting in our data set which has only a modest number of observations. In trimming the number of variables, we considered both the decrease of the LOOCV error of the model and the *p* value of the additional variable (calculated by the two-tailed *t* test under standard assumption). For convenience we chose *p* value of 0.05 as the cutoff point.

3. Results

The metrics (independent and dependent variables) used in the CVSRA were chosen from a subset of PCs (derived metrics) along with several of the original metrics that did not have high correlations with other raw metrics (Tables 1 and 2). The cumulative variance proportions of each PC vary between the derived metrics (Table 1). For instance, PC1 of the water resources metrics explains 52% of the total variance, with PC2 adding another 19% to the total variance explained. Although the absolute magnitude of the variances varies among the different subset countries, the standardized weights were generally consistent for the PCA subset combinations (Table 1). For example, the loadings of the water resources PCs indicate that PC1 primarily captured availability dimensions of water resources, while PC2 captured variability dimensions of water resources for all four combinations of subset countries. Two PCs derived from a group of correlated metrics can capture at least 71% (such as the six metrics of water resources domain in the Water subset) or as high as 92% of the total variance (the six governance indicators of in the energy data set). For the measurable outcomes of FEW services and health in the second and third domains, one PC can explain at least 63% (the four young age malnutrition metrics in the FEW subset) or up to 97% of the total variance (the two energy usage metrics of energy services domain in the FEW subset) for that particular data set. The results indicate that the PC scores we used in the regression analyses can adequately represent the characteristics of the metrics and data while meeting the purposes of dimensionality and covariance reduction. The described behaviors of the PCs were consistent throughout the PCAs for the country subsets for the individual resources (water, energy, and food) as well as cross-sectoral and overall FEW subsets (Table 1).

In the direct sectoral analysis, SG metrics such as governance quality, political stability, and GDP per capita are the primary metrics capturing conversion of resources to services; access to drinking water and some of the food-specific access metrics are significant variables in the services to health outcomes (Figure 7). All models, including independent and dependent raw and derived metrics used, are listed in Table S4. When cross-sectoral linkages are considered, the fossil fuel reserves are significant predictors for improved access to sanitation as well as food production variability; infrastructure variables such as rail lines density and land equipped with irrigation also emerge as significant for food utilization and energy usage and malnutrition outcomes; food services variables are significant variables for malnutrition and air pollution-attributed deaths (Table 3). Similar patterns are present in the FEW nexus linkages analyses as in the cross-sectoral linkages (Figure 8). No significant metrics emerged for food supply variability in either the direct sectoral

Table 1
Variance Explained by Principal Components

Sector	Domain	Derived metric	Explained variance (%)	Subset (*n*)
W	R	Water availability	52	W (38)
			50	E, W-E (20)
			48	F, W-F (21)
			57	FEW (13)
W	R	Annual and seasonal variability	19	W (38)
			23	E, W-E (20)
			19	F, W-F (21)
			20	FEW (13)
E	S	Energy usage	96	E, E-W (20)
			97	E-F, FEW (13)
F	R	Agricultural area	59	F, F-W (21)
			52	F-E, FEW (13)
F	R	Land use	29	F, F-W (21)
			39	F-E, FEW (13)
F	S	Food utilization	80	F, F-W (21)
			83	F-E, FEW (13)
F	S	Protein balance	72	F, F-W (21)
			74	F-E, FEW (13)
F	H	U5 malnutrition	72	F, F-W (21)
			63	F-E, FEW (13)
SG	SG	Overall quality of governance	72	W (38)
			81	E, W-E (20)
			72	F, W-F (21)
			79	FEW (13)
SG	SG	Political stability	13	W (38)
			11	E, W-E (20)
			17	F, W-F (21)
			15	FEW (13)

Note. Although the number of countries vary, similar percentage of variance is explained in the different sectoral and cross-sectoral analyses. Sectors refer to water (W), food (F), or energy (E) or socioeconomic and governance (SG), while domain refers to resources (R), services (S), or health (H). The subset column notes the combination of countries used in the principal component analysis.

or FEW nexus analyses. Overall, SG and infrastructure metrics were the predominant explanatory variables in resources-services paths, while FEW-related services variables were the dominant explanatory variables for FEW-related health outcomes (Figure 9).

4. Discussion

The FEW nexus is characterized by complex factors and dynamics. The FEW-RSH framework aims to untangle the diverse influences by distinguishing three distinctive domains: natural resources, accessibility to critical services, and associated health outcomes (Figure 1). A data-driven quantitative approach guided by the framework was implemented to understand the primary drivers influencing the FEW nexus in SSA countries. Direct and cross-sectoral linkages were evaluated using a CVSRA and a FEW literature summary (Appendix A) was leveraged to understand nuances that may have been overlooked in analysis of national-level data sets.

Interestingly, most of the natural resources variables did not emerge as the most significant predictors in the statistical analyses, highlighting the general abundance of natural resources in these countries (Figures 7

Table 2
Variables Used in the FEW Data Analysis

Sector	Domain	Metric	Unit	Source
W	R	Water availability[a]	—	CRED and Guha-Sapir (2017) and FAO (2016)
		Annual and seasonal variability[a]	—	CRED and Guha-Sapir (2017) and FAO (2016)
W	S	Access to drinking water	%	FAO (2016)
		Access to sanitation	%	FAO (2016)
W	H	U5 diarrhea-caused deaths	%	UNICEF (2018)
E	R	Nonfossil fuel production[a, b]	Mtoe/cap	IEA (2015)
		Fossil fuel production[a, b]	Mtoe/cap	IEA (2015)
		Total fossil fuel reserves[b]	Mtoe/cap	World Energy Council (2016)
		Fuel reserves: oil share	%	World Energy Council (2016)
		Fuel reserves: gas share	%	World Energy Council (2016)
E	S	Energy usage[a]	—	United Nations (2017) and World Bank (2018b)
E	H	Air pollution-attributed deaths	%	WHO (2018a)
F	R	Agricultural area[a]	%	FAO (2018)
		Land use[a]	%	(FAO, 2018)
F	S	Food utilization[a]	—	FAO (2018)
		Protein balance[a]	—	FAO (2018)
		Food supply variability	kcal/cap/day	FAO (2018)
		Food production variability	Int$/cap	FAO (2018)
F	H	U5 malnutrition[a]	—	FAO (2018)
G	SG	GDP per capita[b]	US$	World Bank (2018b)
		Education index	-	United Nations (2013)
		Governance quality[a]	-	Kaufman and Kraay (2015)
		Political stability[a]	-	Kaufman and Kraay (2015)
		Rural population	%	FAO (2016)
E	SG	Import export difference[a]	Mtoe/cap	IEA (2015)
F	SG	Rail lines density[b]	lines per 100 km^2	World Bank (2018b)
		Arable land with irrigation[b]	%	FAO (2018)
		$ Food imp./merch. exp[b]	ratio, 3-year avg	FAO (2018)
		Cereal import dependency ratio	%	FAO (2018)

Note. Sectors refer to water (W), food (F), energy (E), or general (G), while domains refer to resources (R), services (S), health (H), or socioeconomic and governance capacity (SG). U5 = children under 5 years of age. [a]Derived metrics. [b]The data have been *log*10 transformed. FEW = food, energy, and water; GDP = gross domestic product.

and 8). Oil reserves were found to be important for access to improved sanitation and food production variability, highlighting the energy dependencies of these FEW services (Figure 8). In general, the routing of resources through the services domain was dominated by socioeconomic and governance capacity variables (Figure 9). GDP per capita, governance quality, and political stability were the most the prevalent for direct sectoral linkages and infrastructure-related variables such as rail lines density and land equipped with irrigation emerged as significant in the FEW nexus analyses. Despite the potential link between the extraction of raw FEW resources with a portion of domestic GDP as in the case of Nigeria (Appendix A), GDP remains an important proxy of a country's financial capacity that influences the provision of FEW services and the FEW-related health conditions. Governance quality was also a significant correlate of diarrhea-caused deaths in the quantitative analysis. Weak governance can result in poor quality of water services that ultimately threatens people's health. Additional support for this interpretation comes from more detailed reports for three countries (Appendix A). Generally, FEW-related health outcomes were more strongly influenced by FEW services, with water and food access issues particularly impacting health in SSA (Figure 8); the significant relationship between food utilization and air quality, in particular, has also been demonstrated using a panel random effect regression in SSA (Zaman et al., 2017). The analyses did not show a connection between the energy services and energy-related health at the country level. However, the FEW

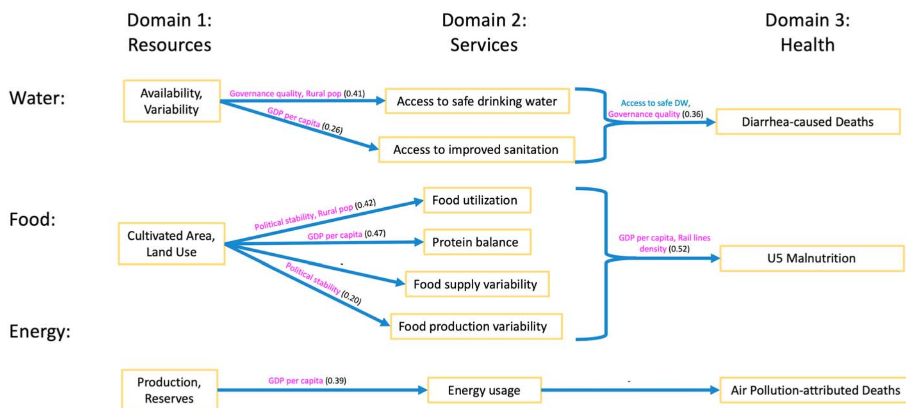

Figure 7. Significant variables from direct sectoral Cross-Validated Stepwise Regression Analysis analyses. The independent variables and the adjusted R^2 are presented on top of each linkage indicated by the blue arrow. Socioeconomic and governance metrics that dominate the resources-services linkages and services together with socioeconomic and governance metrics are the significant variables in the services-health linkages. GDP = gross domestic product.

literature summary for three countries in Appendix A revealed that indoor air pollution caused by the lack of clean cooking in rural areas leads to health inequality issues at the subnational level.

The statistical findings are generally consistent with the FEW nexus summaries of the three countries in Appendix A. Specifically, Senegal and Nigeria have sufficient raw resources (Table 4) but lack capacities in physical infrastructure and treatment/processing technology that limit people's access to FEW services. The

Table 3
Significant Variables in the Cross-Sectoral and FEW Nexus Linkages Identified by the CVSRA Analyses

Sector	Domain	Outcome	Sectors analyzed	Significant variables
W	S	Access to safe drinking water	W-E	Rural pop, governance quality, political stability (0.86)
			W-F	—
W	S	Access to improved sanitation	W-E	Fossil fuel reserves: oil share, GDP per capita (0.55)
			W-F	—
F	S	Food utilization	F-W	Rural pop, political stability (0.42)
			F-E	Rail lines density, land equipped with irrigation (0.48)
F	S	Protein balance	F-W	GDP per capita (0.47)
			F-E	GDP per capita (0.69)
F	S	Food supply variability	F-W	—
			F-E	—
F	S	Food production variability	F-W	Political stability (0.20)
			F-E	Fossil fuel reserves: oil share (0.28)
E	S	Energy usage	E-W	GDP per capita (0.39)
			E-F	Education index and rail lines density (0.81)
W	H	Diarrhea-caused deaths	W-E	Governance quality (0.23)
			W-F	Governance quality (0.31)
F	H	U5 malnutrition	F-W	GDP per capita, rail lines density (0.52)
			F-E	Protein balance, food supply variability (0.67)
E	H	Air pollution-attributed deaths	E-W	—
			E-F	Food utilization (0.57)

Note. In addition to the general SG metrics, fossil fuel reserves and infrastructure-related SG metrics are also significant variables in the cross-sectoral linkages. Sectors refer to water (W), food (F), or energy (E), while domain refers to services (S) or health (H). For readability, the significant variables were color coded by domain: socioeconomic and governance (purple), food (green), and energy (orange). FEW = food, energy, and water; CVSRA = Cross-Validated Stepwise Regression Analysis; GDP = gross domestic product.

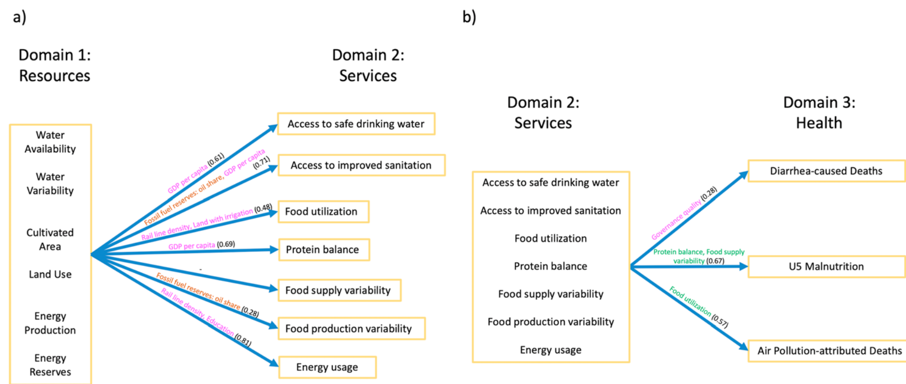

Figure 8. Significant variables between (a) resources and services domains and (b) services and health domains from food, energy, and water nexus Cross-Validated Stepwise Regression Analysis analyses. The independent variables and the adjusted R^2 are presented on top of each linkage indicated by the blue arrow. In addition to the general presence of socioeconomic and governance metrics, infrastructure and services metrics are also present in the food, energy, and water nexus linkages analyses. Food services metrics are important variables for both food and energy-related health outcomes in the food, energy, and water nexus linkages. GDP = gross domestic product.

quantitative results also indicated that infrastructure variables are more dominant than resources variables in the resources-services paths (Figure 9). Indicators related to governance and socioeconomic conditions are higher for South Africa than for Senegal and Nigeria (Table 4). Although FEW services are also better in South Africa, health outcomes are not markedly different among the three countries in the FEW literature summary (Table 4). Political instability from regional conflict also had an impact on infrastructure performance and government functions, especially in Nigeria and South Africa. The CVSRA also revealed that political instability is an important determinant to Water and Food Services (Table 3). Good governance is especially important for addressing cascading failures across sectors (e.g., power outages that impact sanitation access and poor cooking practices leading to indoor pollution). The quantitative results confirm the importance of governance as the second most dominant subcategory of variables in both resources-services and services-health paths (Figure 9). These issues are best addressed through an integrated management of infrastructures by governing institutions (Cai et al., 2018; Lele et al., 2013). The country profiles also highlighted another geographic disparity overlooked in the national-level data: urban-rural disparities. There is a consistent inequality of FEW services between rural and urban regions in all three countries. Limited physical infrastructure capacities (e.g., pipelines and railroads) exacerbate these differences by reducing the transfer of resources from abundant to scarce regions (Burgess & Donaldson, 2010).

The education level of a country may affect the FEW nexus as well. Education was identified as a significant determinant for energy usage using CVSRA. Furthermore, the FEW literature summary in Appendix A

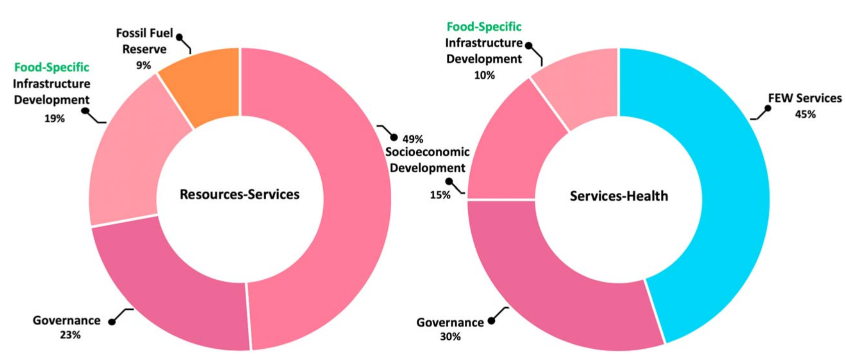

Figure 9. Percentage of significant variables categorized by domain for both direct and cross-sector linkages in the resources-services models (left) and services-health models (right). SG metrics are colored in variations of purple to indicate different subcategories, orange refers to the energy resources metrics, and sky blue indicates the FEW services metrics. SG metrics dominates the routing of resources through the services domain, while FEW services along with SG metrics affect the services to health outcomes. SG = socioeconomic and governance; FEW = food, energy, and water.

Table 4
Data Summary of Senegal, Nigeria, and South Africa

Metric	Unit	Senegal	Nigeria	South Africa
Precip	mm/year	690	1,200	500
ERsv	toe/cap	0	52	390
AraLand	hac/cap	0.21	0.19	0.23
GDP/cap	$/cap	960	2,200	5,300
EduInd	percentile	13th	19th	37th
GovEff	percentile	39th	17th	65th
PltSta	percentile	42nd	7th	40th
WH	% population	8.9	10	8.7
EH	% population	1.6	2.6	2.4
FH	% population	19	33	24
ruPop	% population	57	52	36

Note. ERsv = total fossil fuel reserves; AraLand = arable land; EduInd = Education Index global rank; GovEff = Government Effectiveness global rank; PltSta = Political Stability global rank; WH = Children Under 5 years old (U5) diarrhea deaths; EH = Deaths attributable to air pollution; FH = U5 who are stunted, ruPop = % rural population.

highlighted the importance of education (especially of the mothers) for impacting U5 stunting, especially in Nigeria.

Investments from domestic GDP (as well as income from foreign companies or aid) are critical for building and maintaining infrastructures and developing GIS applications and other pioneering technologies to increase the security and quality of FEW services (Lele et al., 2013). Improving agricultural services (e.g., by reducing food supply variability), in particular, has been recognized to have a significant impact on poverty in SSA (Ozturk, 2017). Improvement of FEW services, such as the improvement of water and sanitation services (Haller et al., 2007), the development and expansion of sustainable energy (Deichmann et al., 2011), and the improvement in irrigation management and agricultural research and development (Thirtle et al., 2003), can also benefit the economy. The case of South Africa highlights, however, that increases in GDP are also associated with higher demand for FEW resources (Sušnik, 2015, 2018). Given climate change impacts on FEW resources, explicit attention is needed to ensure that economic growth pathways incorporate environmental sustainability in SSA (Cumming & von Cramon-Taubadel, 2018).

Although the findings from the data analysis are consistent with the FEW literature summary of the three countries, there are various limitations of the current approach. Notably, this study took a static view of the FEW system in SSA, with temporal variabilities of a country usually represented by a single metric, such as interannual and seasonal variabilities in water resources or production and supply variabilities of food resources. Metrics used in the analysis were not collected at the same time; there were some cases where the year of the metric for a specific country did not match the dates of other countries. Improved data quality and availability would enable better tracking of changes in the different countries' systems over time as well as address issues of collinearity in the metrics. Other techniques such as agent-based modeling can be used to simulate the dynamic relationships between the resources, services, and health domains of FEW sectors (Bonabeau, 2002). Our analysis indicates that in such models, socioeconomic and governance metrics need to be explicitly considered. This approach could be used to evaluate the impact of different adaptation strategies to future changes in climate, urbanization, and other potential disruptions as well as enable incorporation of insights from survey-based and other field methods (Gunda et al., 2017).

This study successfully demonstrates the value of the FEW-RSH framework for facilitating the identification of significant factors influencing FEW nexus dynamics in SSA. The data-driven approach and FEW literature summary both highlighted the importance of considering socioeconomic and governance dimensions of FEW security. The FEW-RSH framework can be implemented at a finer scale (e.g., within countries or cities) to capture further nuances where needed. Future research could also use other techniques such as simulations to evaluate dynamic relationships and further our understanding of the evolving FEW nexus.

Appendix A: Few Literature Summary of Selected Countries

In addition to the quantitative data-driven approach, we compiled literature summaries for three of the SSA countries to further explore FEW dynamics and test and verify the strength and limitations of the quantitative approach. These "country profiles" allow us to delve more deeply into the primary dynamics influencing FEW nexus outcomes of three countries that have different values of the country-level variables that we use. Specifically, for three countries we consider characteristics such as regional climate and geographic variations that may or may not be captured in the country-level data to highlight both consistencies with the data-driven results and potential limitations of a country-level data analysis. Nigeria, Senegal, and South Africa were selected for the FEW literature summary, because these countries capture the diversity in GDP and natural resources in SSA and all had data for all FEW-related metrics. Senegal, Nigeria, and South Africa are located in the west, middle, and south of the study region with distinctively different climate and natural resources reserves, and per capita income is in the relatively low, middle, and high range among the 38 SSA countries included in the study, respectively (Table 4). For each country, peer-reviewed articles, papers from nongovernmental organizations, government reports, and other credible media sources were reviewed to better understand the direct and cross-sectoral linkages between the FEW domains in SSA. The findings from the quantitative analyses and literature summaries were compared to identify FEW areas that require further exploration.

A.1. Senegal

Senegal is a country with relatively limited FEW resources. The country has a long-term average of 700 mm of annual precipitation, 3.2×10^6 ha of arable land, but no fossil fuel reserves. Although the economy is growing and on the ascending trend, the GDP per capita and the education index are still low (Table 4). However, Senegal has a relatively effective government with limited instability, violence, and terrorism issues (Kaufman & Kraay, 2015).

Urban-rural disparities in FEW services have been a common issue for decades; Senegalese people living in urban areas consistently have better access to water and sanitation services, more electricity supply, and better access to food (Nordman, 2018; WFP, 2018b; World Bank, 2018a). Due to income inequality and lack of remediating policies, rural people who cannot afford better FEW services often use biomass for cooking, suffer from food insecurity, and utilize unsafe water (Diallo, 2017; Nordman, 2018; WFP, 2018b). The water utilities in Senegal are also vulnerable to power outages (Adigbli, 2008). Moreover, Senegal's strong seasonal climate and frequent inclement weather events make it challenging to have consistent access to both water services and food services (CRED & Guha-Sapir, 2017). The geographic proximity of Senegal to the Saharan Desert and the Atlantic Ocean makes the arable land in the country prone to floods, droughts, desertification, and salinization (WFP, 2018b).

The climate in Senegal not only impacts FEW services but also affects FEW-related health outcomes. For example, researchers studied the prevalence of diarrhea in urban areas of Dakar and two suburbs and found a high prevalence of rotavirus infections in the dry season, while bacterial infections dominated during the wet season (Sambe-Ba et al., 2013). Their work highlights the potential risks of flooding for exposing environmental pathogens to people directly and indirectly from contaminated water and food. Due to higher income inequality and limited access to food, children in rural areas are more likely to be affected by stunting in the country (USAID, 2014).

Despite these challenges, Senegal continues to make progress on the quality of the FEW services, closing the urban-rural gap, and improving peoples well-being. This is primarily through a collaborative effort among partner agencies, including utilities, health care sectors at all levels, financial institutions, government, public-private partnerships, and international aid organizations such as the World Bank and Red Cross (Diallo, 2017; World Bank, 2018a).

A.2. Nigeria

Nigeria is a country with abundant FEW resources. The country has a long-term average of 1,000 mm of annual precipitation, 10 billion tonnes of oil equivalent (toe) of oil and gas reserves, and 34×10^6 ha of arable land. Although Nigeria has the largest economy in Africa, with the largest population, the per capita GDP ranking is in the middle for SSA countries while education is low (United Nations, 2013). The country faces significant challenges in political stability and government effectiveness as it is ranked low at 7th and 17th percentiles in the world, respectively (Table 4).

Although the economic conditions are relatively strong, Nigeria still lacks essential infrastructures and financial capacity to provide FEW services (Food Security Portal, 2018; United Nations, 2014). Despite investments, drinking water supply improvements are slow growing, while sanitation access is decreasing over time (AMCOW, 2011). Nigeria has more than sufficient natural and human resources to grow agricultural products; however, the country experiences deficiencies in food and is heavily dependent on food imports (Food Security Portal, 2018; Matemilola & Elegbede, 2017). Regional conflicts and domestic violence in the northeastern and other parts of Nigeria have not only seriously disrupted the local FEW services but have also displaced a significant number of people and local workforces in FEW sectors (Strauss Center, 2018; WFP, 2018a). Nigeria has a significant amount of fossil fuel reserves and a significant potential in other renewable energy sources (i.e., hydropower and solar); however, the lack of electrical power supply and refining technologies to process crude oil has made many industrial operations unfeasible (Borok et al., 2013).

Nigeria faces serious FEW-related health issues, such as diarrhea, indoor, air pollution, and malnutrition prevalence among children under the age of five (U5). Although diarrhea has decreased by 20% over a decade in Nigeria, over a hundred thousand U5 deaths were attributed to diarrhea in Nigeria in 2015, accounting for 20% of the global U5 diarrhea-caused deaths (Troeger et al., 2017). Some urban areas in Nigeria have built water treatment plants and deliver treated water to the people. This has reduced the presence of *Escherichia coli* at the taps suggesting the effective removal of microbial contaminants, but heavy metal introduced during the distribution process is posing a greater risk to human health (Etchie et al., 2013). Health disparities are present at the regional scale in Nigeria; some states have a much higher percentage of stunting than other states (USAID, 2018b). In particular, regions with more educated mothers have lower U5 stunting issues, while also present in Senegal, this dynamic is more prevalent in Nigeria (USAID, 2014, 2018b).

After failing to meet the United Nations Millennium Development Goals, the Nigerian government has acknowledged that proper management and effective policies were key to fully utilizing the existing infrastructures, resources, and financial investments. Since then, the government has undertaken a series of reforms such as privatization of the water services sector, enhancement of regulations, and function clarification of responsibilities for government institutions to improve FEW services (AMCOW, 2011).

A.3. South Africa

South Africa has limited water resources, with annual precipitation less than 500 mm. In contrast, the country has 21 billion toe of coal reserves and 13×10^6 ha of arable land. South Africa is one of the top economies in SSA, and the nation ranks high at the 65th percentile rank for government effectiveness and at the 40th percentile rank of political stability globally (Table 4).

South African policy is to provide free access to basic water and electricity (6,000 L of water/household/month and 50 kWh of electricity/household/month for indigent households) as well as basic access to affordable food. However, the nation faces challenges in implementing the policy effectively (Gladwin-Wood & Mathebula, 2016; Muller, 2017). For example, although there are tariffs imposed on high consumption, high water demand and usage in richer parts of the country have led to an unstable and decreasing supply of water for the poorer regions. The affected areas predominantly tend to be rural areas with black communities, which have been historically ignored by service providers even though South Africa became a democracy in 1994 (ANA, 2016; Muller, 2017; Naicker, 2015). The recent Cape Town water crisis highlights that although infrastructure (such as desalination plants) is being developed, the nation will likely continue to face water shortages (Dawson, 2018; Shelly, 2018; Scott, 2018). Climate change, in particular, is expected to pose a significant risk to South Africa's water-dependent economy and the affordability of FEW services in the future (Misselhorn & Hendriks, 2017; Mission 2017, 2017; Muller, 2017). The energy sector also faces similar infrastructure challenges from overloading and power outages due to increasing demand, underinvestment, and maintenance failures (Hedden, 2015; Trollip et al., 2014).

Besides its impact on FEW services, water stress is a significant risk factor for health issues in the country. During the Cape Town water crisis, for example, the citizens were requested to heavily conserve water to avoid a Day-Zero disaster, leading to poor sanitation and personal hygiene as well as severe health risks such as dehydration and heat stroke (Mash et al., 2018). Indoor air pollution caused by smoke from burning wood during cooking is a common energy-related health issue for all three countries in the qualitative analyses, leading to many adverse health effects including eye infections, acute and chronic respiratory diseases, birth weight reduction, and cancer (Anozie et al., 2007; Bensch & Peters, 2017; Vegter, 2016). In South Africa, poor indoor air quality is exacerbated by ambient air pollution, which exceeds the particulate matter 2.5 limit set by local and international standards in a majority of the country. The pollution is particularly high in low-income and heavily populated areas around townships, where coal production is concentrated (Altieri & Keen, 2016). Although there are national standards and legislation focused on regulating and improving air quality in South Africa, the policies have been criticized for being too lenient and for lack of enforcement (Hugo, 2018).

South Africa has legislative support and fairly comprehensive regulations as well as the technical expertise and financial capacity to improve FEW services. However, compliance of service providers with and enforcement by government officials of the laws and regulations need to be significantly improved. It would also be advantageous for South Africa to partner with nearby nations and to use international aid to further improve the quality of FEW services and people's well-being through trade and capacity development (USAID, 2018a).

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