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Advancing the Food-Energy−Water Nexus: Closing Nutrient Loops in Arid River Corridors

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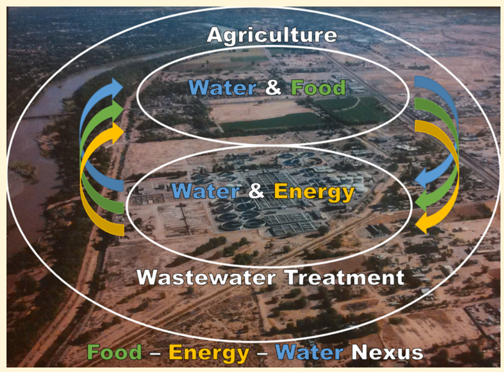
Supporting Information

ABSTRACT: Closing nutrient loops in terrestrial and aquatic ecosystems is integral to achieve resource security in the food-energy-water (FEW) nexus. We performed multiyear (2005−2008), monthly sampling of instream dissolved inorganic nutrient concentrations (NH_4−N, NO_3−N, soluble reactive phosphorus-SRP) along a ~ 300-km arid-land river (Rio Grande, NM) and generated nutrient budgets to investigate how the net source/sink behavior of wastewater and irrigated agriculture can be holistically managed to improve water quality and close nutrient loops. Treated wastewater on average contributed over 90% of the instream dissolved inorganic nutrients (101 kg/day NH_4−N, 1097 kg/day NO_3−N, 656 kg/day SRP). During growing seasons, the irrigation network downstream of wastewater outfalls retained on average 37% of NO_3−N and 45% of SRP inputs, with maximum retention exceeding 60% and 80% of NO_3−N and SRP inputs, respectively. Accurate quantification of NH_4−N retention was hindered by low loading and high variability. Nutrient retention in the irrigation network and instream processes together limited downstream export during growing seasons, with total retention of 33−99% of NO_3−N inputs and 45−99% of SRP inputs. From our synoptic analysis, we identify trade-offs associated with wastewater reuse for agriculture within the scope of the FEW nexus and propose strategies for closing nutrient loops in arid-land rivers.



1. INTRODUCTION

Projected rises in human population (over 9 billion by 2050) and standards of living have accentuated the importance of the interconnections among food, energy, and water (FEW) resources and the need for holistic approaches (the FEW nexus) to promote their production, distribution, and consumption.[1−3] Accordingly, there is an urgent need to identify and quantify synergies and trade-offs pertaining to the FEW nexus that support strategies to sustain human populations while minimizing natural ecosystem degradation.[4,5] This is especially true for arid-land regions (i.e., arid, semiarid, and dry subhumid), which hold over one-third of the global population, nearly half of the world's livestock and cultivated land, and are facing multiple external pressures (e.g., rapid population growth, food insecurity, and climate change) that stress FEW resources.[6−8] While the FEW nexus has recently emerged as a conceptual approach to address global resource challenges, achieving resource security requires research and environmental policy focused on both local and regional scales.[9]

Isolated management of each of the FEW sectors, the status quo, has resulted in unsustainable, unclosed nutrient loops. For example, consider the movement of nitrogen (N) and phosphorus (P) through processes associated with food production and consumption. Synthetic fertilizers are manufactured from finite resources (i.e., mineral phosphate)[10] and energy intensive processes (i.e., Haber-Bosch process)[11] to supply bioavailable nutrients to agricultural soils. Widespread overapplication of fertilizers results in nutrient losses to aquatic ecosystems,[12,13] which disrupt nutrient cycles and cause eutrophication.[14−16] Additionally, following fertilizer and food production, human consumption and excretion concentrate nutrients in wastewater effluents. However, rather than being recycled or utilized in this concentrated form, effluent is regularly discharged into freshwater ecosystems, which both irretrievably dilutes a valuable, finite resource and, paradoxically, contributes to eutrophication of freshwater ecosystems. Although the current operational paradigm for wastewater treatment plants (WWTPs) is to implement nutrient removal

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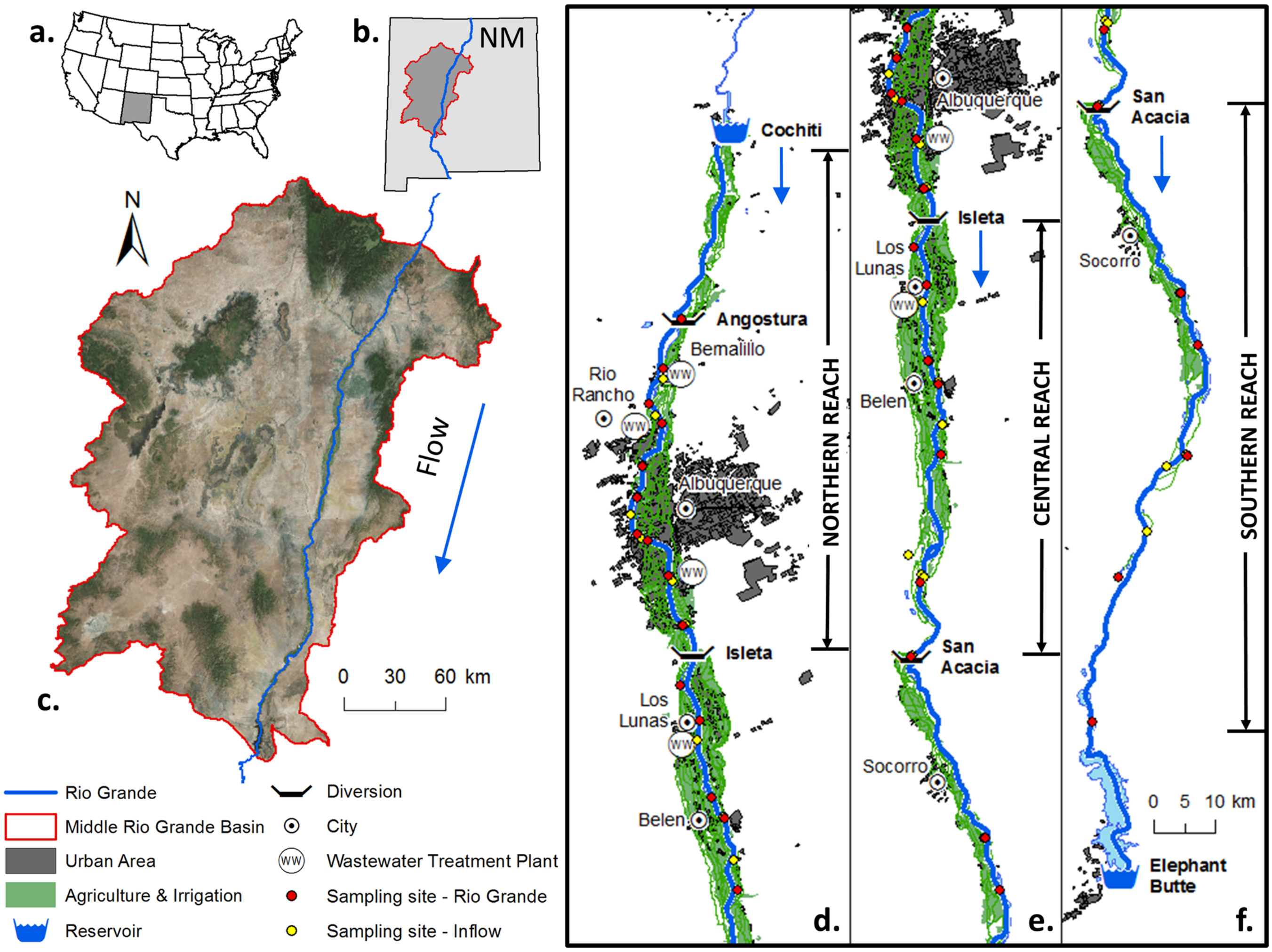

Figure 1. a. New Mexico (NM), USA; b. Middle Rio Grande Basin (MRGB), NM; c. satellite imagery of the arid-land MRGB (~50,000 km^2) and Rio Grande (306 km); and Rio Grande subreaches for this study: d. Northern reach (Cochiti – Isleta, 103 km), e. Central reach (Isleta – San Acacia, 85 km), and f. Southern reach (San Acacia – Elephant Butte, 118 km). Panels d, e, and f show land use (urban and agricultural), sampling sites, and key features (cities, wastewater treatment plants, reservoirs, and diversions) along the Rio Grande in the MRGB. Maps were created using ArcGIS software by Esri. ArcGIS and ArcMap are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved.

technologies to reduce nutrient pollution (advanced or tertiary treatment processes), this stage of treatment is highly energy intensive, requires large capital costs, and depletes available nutrients which are an important and limited resource.[17,18] Shifting to a holistic perspective, however, WWTPs should be seen as a reliable supply of both water and nutrient resources for agriculture rather than simply as a waste disposal service.[19−23] For example, instead of targeting year-round conversion of nutrients from biologically available forms (e.g., ammonium and organic nitrogen) to biologically unavailable forms (e.g., dinitrogen gas) to reduce aquatic nutrient pollution, the operation of WWTPs may be tailored to facilitate nutrient recovery for crop production. This approach would yield energy savings in the production and application of fertilizers, and in the operation of WWTPs. Thus, identifying strategies that close nutrient loops by recycling nutrients from wastewater sources into agricultural production has strong potential to advance the FEW nexus.

We propose that in arid-land river corridors, connections between water resources, food production, and nutrient cycles provide unique opportunities to close nutrient loops and subsequently manage multiple sectors of the FEW nexus. WWTPs are often the dominant source of bioavailable nutrients exported from arid-land rivers[24−27] and, therefore, directly recycling wastewater nutrients into agriculture through irrigation may considerably reduce nutrient export, improving water quality and closing nutrient loops. Reclaiming wastewater resources also addresses challenges created by limited water supply, high irrigation rates, and resulting water scarcity in arid-lands.[28,29] Furthermore, arid-land river corridors typically contain high densities of regulatory structures (e.g., dams and weirs) and irrigation infrastructure (e.g., supply canals and drainage ditches) that enhance nutrient retention in river systems via increased residence times and contact with biochemically heterogeneous flowpaths.[7,30−34] Altogether, these features produce high rates of nutrient retention in arid-land basins,[24,35−37] suggesting that well-defined strategies for wastewater reuse can begin closing nutrient loops with implications for holistic resource management of the FEW nexus.

We investigated the physicochemical viability of an irrigated agricultural system to use reclaimed wastewater resources to meet agricultural water and nutrient requirements in the Middle Rio Grande basin (MRGB) (New Mexico), which

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sustains a metropolitan area of approximately one million people, including the City of Albuquerque.[38] Our research objectives were to (1) generate a nutrient budget for the Rio Grande and the adjacent irrigation network within the MRGB to characterize the net source/sink behavior of wastewater sources and irrigated agriculture, (2) identify and quantify trade-offs associated with arid-land wastewater reuse for agriculture within the scope of the FEW nexus, and (3) propose effective nutrient management for advancing the FEW nexus in arid-land basins.

2. MATERIALS AND METHODS

Site Description. The MRGB of central New Mexico is a major sub-basin of an arid-land river that experiences competing management interests between urban centers, irrigated agriculture, and environmental flows. The MRGB (~50 000 km^2) is defined by a 306 km reach of the Rio Grande, which is bounded upstream by the outfall of Cochiti Reservoir and downstream by the inflow to Elephant Butte Reservoir (Figure 1). The MRGB is predominantly classified as shrubland (39%) and rangeland (32%),[39] however, vegetation and land use in the MRGB historic floodplain differs dramatically from the rest of the basin. Agricultural land use occurs on 32% of the MRGB floodplain, which is primarily alfalfa, pasture grasses, and fallow fields. Approximately 54% of the floodplain is currently undisturbed while the remaining 14% of the floodplain has undergone urban development.

The hydrology of the MRGB is controlled by a series of impoundments and diversions that restrict flooding and supply irrigation under the management of the U.S. Army Corps of Engineers and the Middle Rio Grande Conservancy District (MRGCD), respectively. The regulation of the Rio Grande by hydraulic structures is common among large arid-land rivers globally.[7] Water entering the MRGB is regulated by releases from Cochiti Reservoir with no significant perennial tributaries or inflows, except WWTP outfalls. Annual peak flows typically occur in May, following snowmelt in the mountainous headwaters, and monsoon precipitation events result in episodic high flows in July-September.[40] Streamflow losses to evapotranspiration and seepage to alluvial groundwater have been estimated to range from 12 to 37% along this reach.[39] During the growing season (March−October), water is diverted into an irrigation network by three low-head dams located 38, 103, and 188 km below Cochiti Reservoir (Angostura, Isleta and San Acacia, respectively) (Figure 1). During growing season months in our study, an average of 17 ± 8 (mean ± standard deviation), 60 ± 27, and 42 ± 25% of the Rio Grande was diverted (or remained diverted) from the main channel into the irrigation network at these respective locations. This extensive irrigation network consists of ~2100 km of irrigation ditches and drains which flood-irrigate ~25 000 ha of cropland.[41] On average, agricultural drains return water to the mainstem Rio Grande ~50 km downstream of where water was diverted from the river. During the nongrowing season (November−February) there are no significant withdrawals for irrigation, with water released from Cochiti Reservoir flowing unimpeded to Elephant Butte Reservoir.

Four WWTPs (Bernalillo, Rio Rancho, Albuquerque, and Los Lunas) discharge directly to the Rio Grande (Figure 1). Most notably, the Albuquerque Southside Reclamation Plant is the leading regional source of nutrient inputs, discharging an estimated load of 980 kg/day of dissolved inorganic nitrogen (NO_3−N + NO_2−N + NH_4−N), at an average flow rate of 2.3 m^3/s.[39,42] Discharge from this WWTP accounts for an average of 12% (range 3−22% monthly in this study) of the flow in the adjacent Rio Grande, although this contribution has been observed to exceed 80% during episodic low-flow periods. The dominance of point-source N loads in the MRGB is consistent with other arid-land rivers previously studied in global analyses.[24−27] During the growing season, the agricultural irrigation network has been shown to act as a N sink through the diversion of the Rio Grande downstream of WWTP outfalls.[39]

Data Collection. We collected grab samples monthly (over a two- to three-day period) from 23 mainstem sites distributed along the entire MRGB reach from September 2005 to January 2008 (28 sampling events). With the recent advent of near-continuous nutrient samplers, it has been demonstrated that monthly sampling frequencies provide sufficient data to characterize mean nitrate concentrations and nitrate fluxes without bias, even in highly dynamic agricultural watersheds.[43] Mainstem sampling sites were located sufficiently downstream of wastewater and irrigation return flows to allow complete transverse mixing as predicted by mixing equations.[44] All samples were collected at approximately mid-depth and as close to the stream thalweg as flows permitted. Samples were collected in 130 mL syringes and immediately filtered in the field through 0.7 μm pore size Whatman GFF filters. Samples were analyzed for ammonium (NH_4−N), nitrate (NO_3−N), and soluble reactive phosphorus (SRP). Filtered samples for NO_3−N and SRP were stored at 4 °C and analyzed within 72 h. NO_3−N and SRP samples were analyzed by ion chromatography (Dionex, Standard Method EPA 300.1, 2). NH_4−N samples were frozen until analysis, which was performed by the phenol hypochlorite method with a 10 cm flowpath.[45] Grab samples were also collected from the four WWTP outfalls: Bernalillo, Rio Rancho, Albuquerque, and Los Lunas (21, 22, 22, and 19 sampling events, respectively). For months when data were not collected from one or more WWTPs, mean NH_4−N, NO_3−N, and SRP loading rates were calculated from the available data for each WWTP and used to estimate nutrient loading for the respective WWTP (sampling events using mean wastewater loading rates are indicated in the Supporting Information (SI) Tables S4−1, S4−2). Sampling events were performed during periods of stable flow with the exception of seven sampling events when unexpected changes in discharge occurred during the sampling period. Only data gathered during stable flow conditions (21 sampling events) were used for analysis, with the exception of WWTPs which were unaffected by changes in discharge. For 15 of the 21 sampling events with stable flow conditions, grab samples were also collected from agricultural drains. During a few summer months, some of the southern sites on the Rio Grande had no discharge so no samples were taken. Discharge data to estimate nutrient loads were obtained from 17 MRGCD gages, 10 USGS gages, and 4 WWTPs.

Aquatic Nutrient Budgets. A mass balance approach was used to generate an aquatic nutrient budget for each sampling event along the MRGB (Figure 2). Steady-state nutrient loads ($\dot{m}$) [MT^{-1}] were calculated as the product of measured nutrient concentrations (C) [ML^{-3}] and mean monthly discharge (Q) [L^3T^{-1}]. The mass balance is represented by eq 1 where subscripts represent in = upstream loading; WW = wastewater loading; ag = agricultural loading; instr = instream processes; and out = downstream export. The net nutrient sources/sinks were attributed to upstream loading, wastewater

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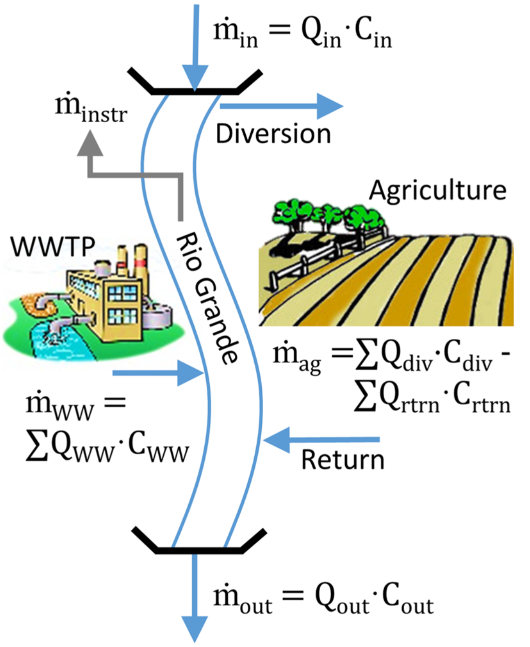

Figure 2. Conceptual mass balance applied to the Rio Grande. Nutrient loads ($\dot{m}$) were calculated as the product of measured nutrient concentrations (C) and mean monthly discharge (Q) for upstream loading (in), wastewater loading (ww), instream processes (instr), agricultural loading (ag), and downstream export (out) for each sampling event.

loading, and the exchanges and reactions along instream (main channel reactions and interactions between surface and ground waters) and agricultural (irrigation channels, crops/soils) compartments. Specifically, the quantities representing input, output, and agricultural loading were calculated directly from obtained data; input (upstream and wastewater loading) and output (downstream export) were determined from individual samples (concentration and discharge) and agricultural loading was estimated by subtracting loads reentering the main channel via agricultural return drains from the loads exiting the main channel at agricultural diversions. Instream processes were calculated from eq 1 as the loss of nutrients not attributable to agricultural loading. Note that upstream and wastewater loading are net sources, agricultural loading can be a net source or sink (i.e., agricultural retention occurs when agricultural loading is negative), and instream processes are assumed to act as a net sink.

$$dm/dt = \underbrace{(\dot{m}_{in} + \dot{m}_{WW})}_{\text{input}} + \underbrace{(\dot{m}_{ag})}_{\text{agricultural loading}} - \underbrace{(\dot{m}_{instr})}_{\text{instream processes}} - \underbrace{(\dot{m}_{out})}_{\text{output}} \quad (1)$$

Aquatic nutrient load calculations were performed for the entire MRGB reach (Cochiti − Elephant Butte, 306 km) and for the three subreaches between diversions: Northern (Cochiti − Isleta, 103 km), Central (Isleta − San Acacia, 85 km), and Southern (San Acacia − Elephant Butte, 118 km) (Figures 1 and 2). Refer to Supporting Information for complete calculations.

3. RESULTS AND DISCUSSION

Aquatic Nutrient Budgets in the MRGB. Wastewater effluent was the primary source of nutrients to the Rio Grande in the MRGB. WWTPs discharged a combined average nutrient load of 1097 ± 282 (mean ± standard deviation) kg/day NO_3−N, 656 ± 146 kg/day SRP and 102 ± 52 kg/day NH_4−N, at a combined average flow rate of 2.6 ± 0.06 m^3/s. The Albuquerque Southside Reclamation Plant (serving ∼0.6 million people) was the primary contributor to WWTP nutrient loads (83% NO_3−N, 92% SRP, 73% NH_4−N). On average, all WWTPs contributed over 90% of the total nutrient inputs to the Rio Grande in the MRGB. Other nutrient sources include the upper Rio Grande and agricultural drains. Water entering from the upper Rio Grande contributed an average nutrient load of 71 ± 122 kg/day NO_3−N, 31 ± 34 kg/day SRP, and 10 ± 19 kg/day NH_4−N. No seasonal trends were observed for nutrient loads from WWTPs or the upper Rio Grande. During nongrowing seasons, agricultural drains were a net source of nutrients, contributing an average load of 131 ± 74 kg/day NO_3−N, 73 ± 11 kg/day SRP, and 19 ± 3.3 kg/day NH_4−N (Figure 3). Each subreach of the irrigation network was a source of nutrients to the Rio Grande during nongrowing seasons.

During growing seasons, the agricultural irrigation network retained an average nutrient load of 454 ± 213 kg/day NO_3−N and 316 ± 152 kg/day SRP, or approximately 37% and 45% of the total NO_3−N and SRP inputs, respectively. Water diverted into the irrigation network in the central and southern subreaches contained elevated nutrient loads due to their location downstream of WWTP outfalls (Figure 1). Loads returned to the Rio Grande by agricultural drains in these subreaches were reduced relative to the load diverted into the irrigation network (Figure 3). The irrigation network in the northern subreach, however, was a source of nutrients during all months. This is likely due to the diversion of low nutrient loads into the irrigation network in the upper portion of the MRGB. The highest rates of agricultural nutrient retention were observed in June−September during growing seasons. These nutrient retention rates varied proportionally to the irrigation rates in the months transitioning between growing seasons and nongrowing seasons (e.g., March and October). For example, sampling during March 2007 suggests that the typical flushing of the irrigation network (water circulation through the network without irrigation) taking place at the beginning of the growing season mobilized relatively high loads of NO_3−N to the Rio Grande.

The primary nutrient sinks in the MRGB were instream processes and retention within the agricultural irrigation network during growing seasons. Instream processes include denitrification, uptake, seepage, and other biogeochemical processes that may occur as water flows through the main channel of the Rio Grande. Instream processes removed on average 460 ± 204 kg/day NO_3−N and 338 ± 197 kg/day SRP or approximately 38% and 48% of the total NO_3−N and SRP inputs, respectively. Given estimates of streamflow losses to evapotranspiration and seepage (12%−37%, see Site Description), instream nutrient processing can be conservatively estimated to remove on average 290 and 213 kg/day NO_3−N and SRP, respectively. Nutrient loads removed by instream processes did not vary significantly (Welch's *t* test, $p \gg 0.05$ NO_3−N and SRP) between growing seasons and nongrowing seasons. On the other hand, the net retention of aquatic

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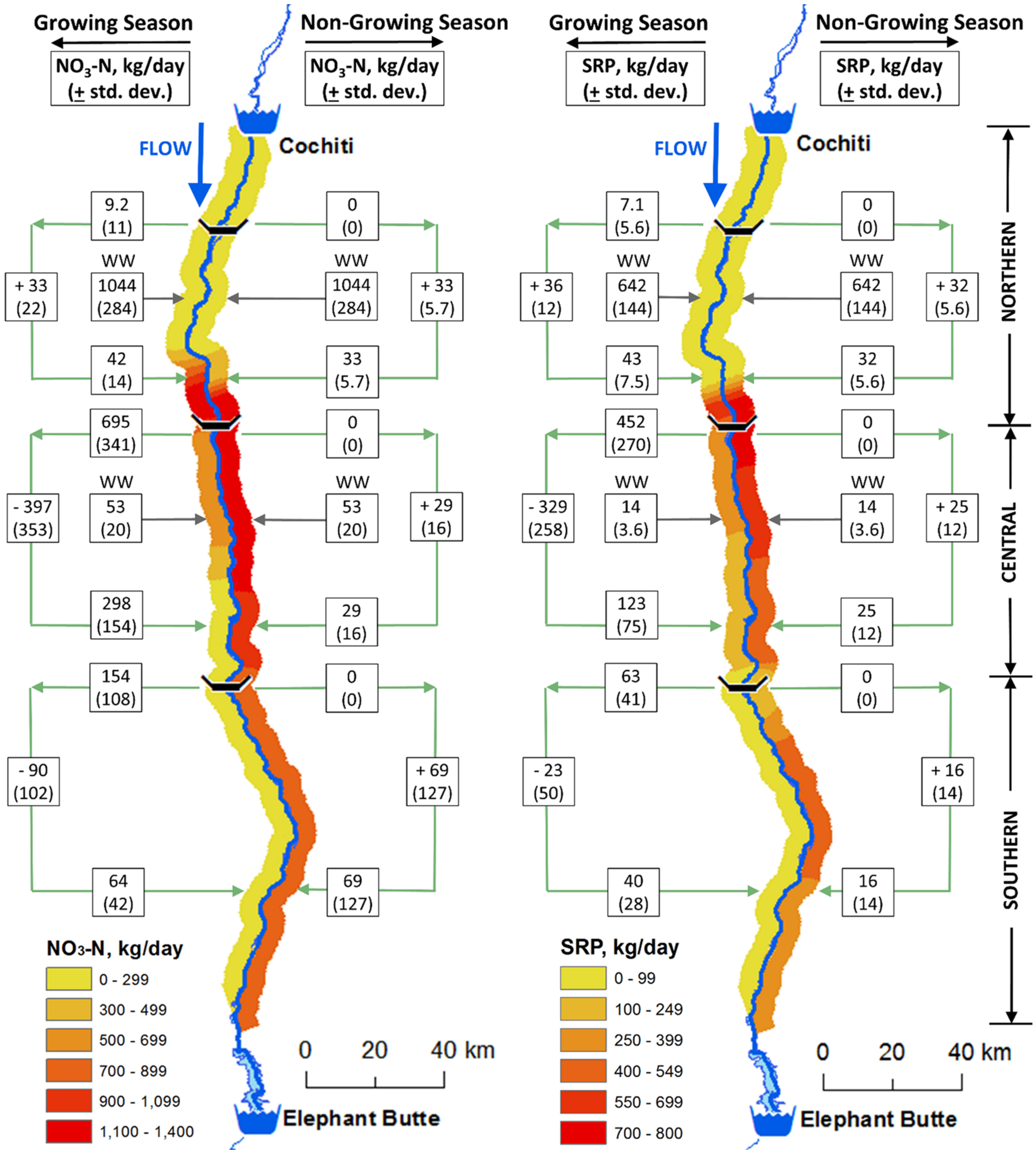

Figure 3. Representative NO3-N (left) and SRP (right) loads (kg/day) along the Rio Grande study reach (306 km). Growing season (May 2006) and nongrowing season (December 2007) months are represented by the left and right river banks, respectively. Mean nutrient loads (+ std. dev.) for agricultural diversion/return flows and WWTP effluent for the study period are shown in boxes.

nutrients (the sum of instream processes and agricultural retention) in the MRGB varied significantly (Welch's *t* test, $p <$ 0.01 NO_3−N, p = 0.01 SRP) between growing seasons and nongrowing seasons due to elevated retention in the irrigation network during agricultural operations (Figure 4). During growing seasons, net retention averaged 77% and 85% of the total NO_3−N and SRP inputs, respectively, with a maximum of 99% for both NO_3−N and SRP inputs. During nongrowing seasons, net retention averaged 26% and 50% of the total NO_3−N and SRP inputs, respectively. Net retention was relatively lower in months transitioning between growing seasons and nongrowing seasons (e.g., March and October) than during the peak of the growing season. This is likely due to reduced agricultural retention which occurs during these transitions. As a result of existing nutrient sinks in the MRGB, the export of nutrients during growing seasons averaged 22% and 15% of the total NO_3−N and SRP inputs, respectively. During nongrowing seasons, downstream export averaged 71% and 48% of the total NO_3−N and SRP inputs, respectively. Analyses of NH_4−N retention were limited by high variability and relatively low loading of this nutrient to the Rio Grande in the MRGB. Net retention averaged 64% of total NH_4−N inputs during the study period (growing and nongrowing season months), however, the contributions from agricultural retention and instream processes were less pronounced than for NO_3−N and SRP. Overall, elevated nutrient retention during growing seasons drastically reduced export from the MRGB (Figures 3 and 4).

Agriculture and Ecosystem Services. In the arid-land MRGB, the FEW nexus benefits from the ecosystem services provided by irrigated agriculture. The attenuation of nutrient loads in the agricultural system provides a valuable ecosystem

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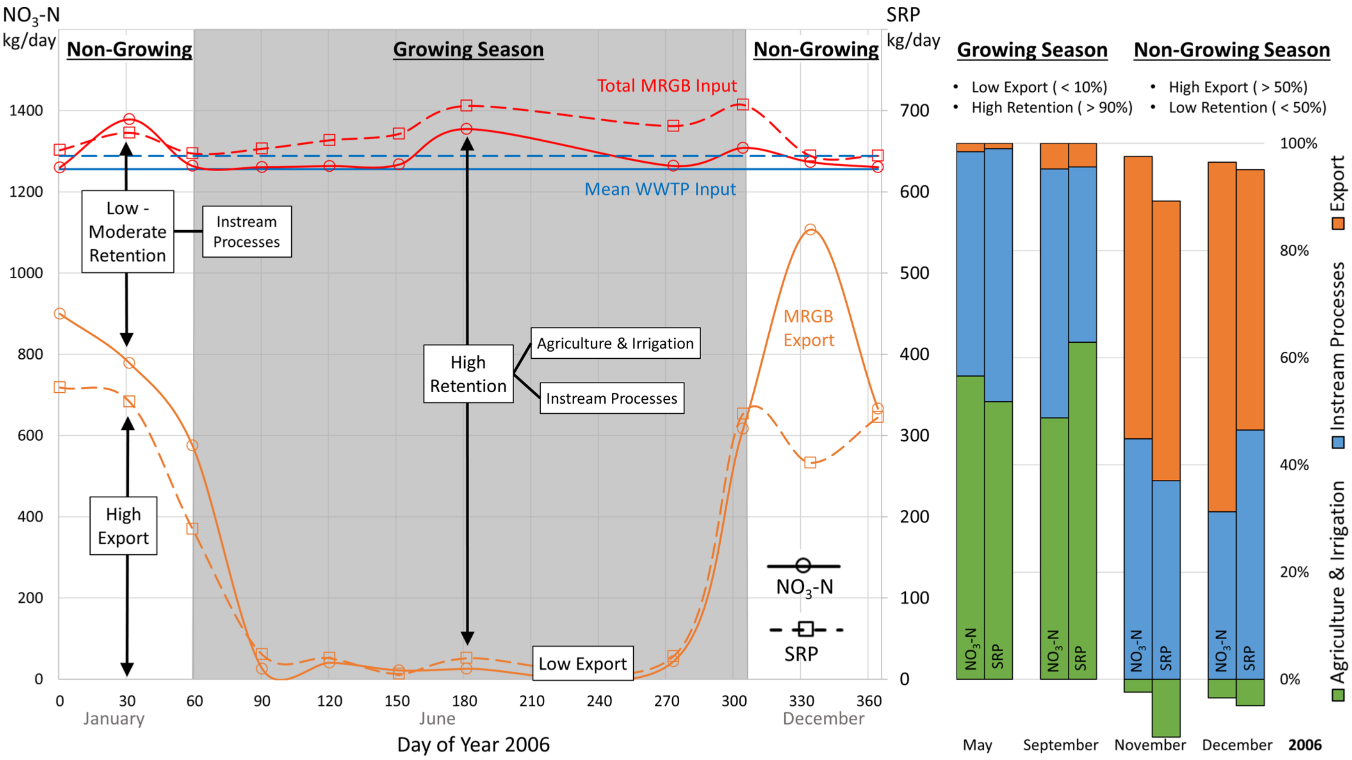

Figure 4. (Left) Aquatic nutrient inputs, retention, and export from the Rio Grande in the Middle Rio Grande basin during 2006. NO_3−N is shown by continuous lines and circles using the left axis; SRP is shown by dashed lines and squares using the right axis. (Right) Nutrient loading partitioned between agriculture, instream processes, and export for growing season (May, September 2006) and nongrowing season months (November, December. 2006). Partitioning is expressed as percentages of total loading for NO_3−N (left columns) and SRP (right columns).

service by improving the water quality leaving the MRGB during growing seasons, limiting eutrophication of downstream water bodies.[46,47] This contrasts to other more humid climatic regions where agriculture is overwhelmingly a nutrient source to receiving waters.[15] Nutrient retention in the MRGB agricultural system is influenced by several factors including: limited N fertilization of dominant crops, flood irrigation practices, and conveyance in the irrigation network. Alfalfa is the dominant crop in the MRGB and requires minimal N application for seedlings (22 kg/ha) and effectively none for mature stands as alfalfa establishes symbiosis with the nitrogen fixing bacteria *Rhizobium*.[48] The low rate of N application in the MRGB limits the supply of N in agricultural soils that may be mobilized to waterways. Alfalfa does require appreciable P application (130 kg P_2O_5/ha) in the MRBG,[49] however, the retention of P fertilizers is likely influenced by sorption. The use of flood irrigation practices introduces several potential pathways for retention as nutrients from wastewater and fertilizer sources are applied to crops. During flood irrigation, water percolates through the soil column into the root zone where uptake of water and nutrients by crops takes place. There, sorption to soil particles may also occur, presenting a mechanism for retaining nutrients, especially SRP.[50−52] This retention mechanism may explain high SRP retention despite the application of P fertilizer. Flood irrigation also simulates natural floodplain conditions that promote denitrification by exposing N-rich water to often oxygen depleted organic-matter rich soils.[53] Additionally, the routing of water through an extensive network of irrigation ditches and drains increases hydraulic residence times and contact between benthic and hyporheic microbes and solutes. Besides increasing contact times, residence time is strongly correlated with nutrient retention in river systems due to biogeochemical processing in aerobic and anaerobic compartments (including denitrification)[54−57] provided sufficient dissolved and particulate organic matter is present, as is the case in most irrigation ditches.[58] Vegetation growth in irrigation ditches has been shown to increase nutrient uptake by providing multiple interfaces for microbial growth and N related processes.[59,60] Finally, prevailing losing conditions causes water to flow from the mainstem of the Rio Grande to the alluvial aquifer where additional nutrient uptake by riparian vegetation occurs before surface water and the remaining nutrients become part of the groundwater system.[61] Together, these factors create favorable conditions for nutrient retention during typical agricultural operations in the MRGB.

Promoting ecosystem services through agricultural management is key to closing nutrient loops and to sustainably achieving FEW resource security in arid-land river corridors.[62,63] In the case of the MRGB, the retention of nutrients resulting from the diversion, conveyance, and irrigation of crops in the arid MRGB is just one example of an ecosystem service provided by the agricultural system. In addition to nutrient retention, the irrigation channels that comprise the irrigation network provide valuable hydrologic, riparian, and agroecosystem functions to the surrounding landscape.[64−66] Seepage from irrigation channels raises local groundwater levels which augments streamflow following the growing season when it is slowly released to the river. Irrigation channels and associated seepage also support areas of riparian vegetation, which improve bank stability, decrease erosion, and create habitat that supports biodiversity in agroecosystems. In arid-land rivers with managed hydrology such as the Rio Grande along the MRGB, overbank flooding and natural floodplain

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processes are limited, however, the use of irrigation channels and flood irrigation practices can simulate this natural hydrology and its associated benefits. Also, the operation and maintenance of these traditional irrigation channel systems, commonly called *acequias*, are of great historical and cultural importance to the region. Thus, the multifunctional nature of these systems in their current operational state (i.e., unlined channels) should be appreciated when considering potential infrastructure modifications (i.e., impervious lining) or land use changes (i.e., conversion of agricultural land). Sustainable advances in food production will require promoting the provisioning, regulating, supporting, and cultural ecosystem services provided by arid-land agroecosystems.

Closing Nutrient Loops—Direct Wastewater Reuse in Arid-Lands. In arid-land rivers such as the Rio Grande, closing nutrient loops will require increasing the amount of nutrients recycled from wastewater effluent (typically the leading nutrient source) into crop production. The role of the agricultural irrigation network as a nutrient sink in the MRGB suggests that direct wastewater reuse for agriculture is an effective strategy to increase recycling of wastewater derived nutrients in arid-land rivers. Currently, wastewater nutrients remaining after advanced treatment processes (i.e., nitrification/denitrification) are indirectly supplied to agriculture by the diversion of the Rio Grande downstream of WWTP outfalls. However, this process of indirect reuse leads to several inefficiencies in the context of nutrient recycling. Once discharged to the river, nutrients are irretrievably diluted by mixing and, therefore, at downstream diversions, the wastewater nutrient load is coallocated between the irrigation network and the downstream river reach. For example, approximately 60% of the river is diverted at the Isleta diversion during the growing season, and the remaining nutrient load can be removed by instream processes or can contribute to downstream nutrient export. Direct wastewater reuse would maximize the amount of wastewater nutrients supplied to agriculture by minimizing nutrient losses to the Rio Grande. Wastewater discharges were consistently lower than agricultural diversions during the growing season in the MRGB, which means that all wastewater could be utilized by agriculture, although additional withdrawals from the river would be needed to augment water supplies. The colocation of WWTPs and the irrigation network in the Rio Grande floodplain would allow for direct wastewater conveyance with minimal required modifications to existing infrastructure. While direct wastewater reuse for agriculture is expected to achieve significant nutrient savings, water savings are unlikely to be observed along the Rio Grande because wastewater is currently being discharged to the river and diverted downstream. Hence, wastewater does not represent a new source of water for irrigation but rather an existing source of water with dissolved nutrients which can be recycled.

There are opportunities for improving nutrient management within the irrigation network. Aquatic vegetation increases nutrient retention in irrigation channels,[59,60] therefore, regulating vegetation may control where nutrients are retained in the agricultural system. For example, minimizing vegetation in supply channels could maximize the amount of wastewater nutrients available to crops during flood irrigation, while accumulating vegetation in drainage channels could attenuate remaining nutrients (not taken up by crops) prior to return to the mainstem river. Although the removal of vegetation may be desirable to maximize nutrient availability during flood irrigation, vegetation should also be considered for its role in improving channel stability and mitigating sediment and nutrient export associated with erosion.[67] Existing irrigation infrastructure could also be modified to increase nutrient retention by adding flow control structures that increase residence times,[68] altering channel geometry to improve retention at high flows,[67] or using restoration structures to enhance hyporheic flow and nutrient cycling.[69] Implementation of such features should occur downstream of agricultural fields (i.e., drainage ditches) in order to attenuate nutrients not retained by crops during flood irrigation. During the non-growing season, the irrigation network could continue to be used to convey wastewater and mitigate nutrient loads returned to the river. This would allow for improved nutrient management throughout the year.

In addition to recycling wastewater nutrients in arid-land rivers, closing nutrient loops will require meeting agricultural nutrient demands through renewable sources. In the MRGB, P fertilizer is recommended for the cultivation of alfalfa, the dominant crop type. Approximately 8000 ha of alfalfa were harvested annually in the MRGB between 2005 and 2007,[70,71] representing a total fertilizer demand of ~1000 Mg P_2O_5 (~450 Mg P). This estimate is representative of current P requirements because of relatively stable production trends in the MRGB. During growing seasons, treated wastewater contributed ~154 Mg SRP (~50 Mg P) or 11% of the recommended P fertilizer for the MRGB. Therefore, under the current treatment conditions, treated wastewater is unlikely to satisfy all the P requirements of alfalfa crops in the MRGB. However, managing wastewater resources for agriculture introduces trade-offs between wastewater treatment and nutrient availability that have potential benefits within the scope of the FEW nexus. For example, reducing advanced wastewater treatment processes to increase nutrient availability for agriculture (i.e., moving from tertiary treatment to secondary treatment) will also decrease energy consumption at WWTPs.[72,73] Raw wastewater has a typical SRP concentration (~10 mg/L) much greater than treated wastewater effluent (2.7 ± 1.4 mg/L SRP in this study). Assuming the above SRP concentration of raw wastewater, the available supply of P from WWTPs located along the MRGB during the growing season can be estimated as ~570 Mg SRP (~186 Mg P), or approximately 41% of the recommended P fertilizer. While these values are likely overestimates for available P fertilizer due to nutrient retention associated with conveyance in the irrigation network, they are meant to illustrate the significant increase in available nutrients by reducing the level of wastewater treatment. Additionally, continual irrigation with nutrient enriched water may increase crop P use efficiency when compared to single application of synthetic fertilizer,[74] thus requiring less overall P. Although decreasing wastewater treatment could increase the quantity of nutrients available for agricultural use, additional renewable sources of P such as livestock manure and food wastes would need to be recycled to completely satisfy nutrient requirements in the MRGB from renewable sources.

Irrigation with wastewater occurs globally, primarily in areas of water scarcity such as the Near East, Australia, and the southwestern U.S.[28,75] Accordingly, wastewater is used to increase food production by augmenting limited water supplies that would otherwise restrict irrigated agriculture. The nutrient content of reclaimed wastewater is commonly acknowledged to benefit soil productivity and crop yields,[76−78] however, managing wastewater nutrients to maximize sustainable

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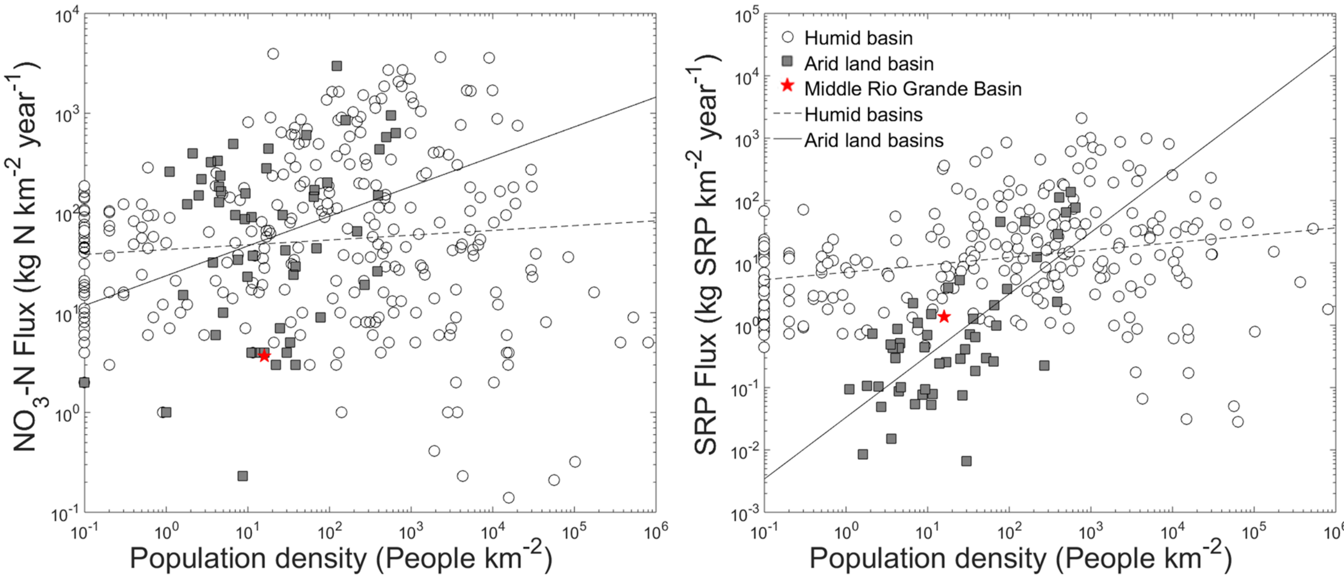

Figure 5. NO_3−N (left) and SRP (right) export (expressed as catchment flux) versus population density for humid (circles) and arid-land basins (squares) including the Middle Rio Grande Basin (stars). Trend lines are shown for humid (dashed) and arid (solid) basins. Trend lines were fit using linear least-squares regression. Data obtained from Alvarez-Cobelas et al.[35,36]

agricultural benefits has received limited attention.[79] With the future direction of wastewater treatment becoming more holistic in terms of resource recovery and environmental sustainability,[22,80] expanding wastewater reuse can help realize these goals through nutrient recycling and energy savings from reduced treatment and fertilizer production and transportation. Additionally, in the MRGB, treated wastewater discharged during the growing season represents an estimated annual fertilizer value of approximately $450,000 in N and $270,000 in P,[81] which illustrates the potential economic benefit of reclaiming wastewater nutrient resources for food production. As noted previously, reducing wastewater treatment can increase these values as more nutrients are made available for agricultural use. While irrigation with reclaimed water can benefit food production by supplying organic matter and nutrients to agricultural soils, additional wastewater constituents must be considered for adverse impacts when using reclaimed wastewater. These constituents include salinity, sodicity, heavy metals, and pathogens, which in high concentrations retard plant water uptake, alter soil structure, increase toxicity, and affect public health, respectively. Wastewater irrigation schemes must address these constituents with special attention to public health, environmental risks, and long-term accumulation in soils.[82,83] Various solutions have addressed these concerns in wastewater irrigation, including diluting wastewater (already practiced indirectly in the MRGB), leaching of constituents through the soil profile, source control (i.e., restricting saline sewer discharges), and wastewater treatment process control.[28,76] Currently, the development and implementation of treatment technologies specifically targeting recovery of nutrient resources for agriculture (in liquid effluents or solid precipitates) while removing adverse wastewater constituents remains a key research area within the FEW nexus. It should also be noted that while it is desirable to maximize the supply of nutrients to agriculture, excessive nutrient inputs can lead to overfertilization of crops with potential detrimental effects to yield, maturity, and disease resistance.[28] Groundwater contamination should also be considered under wastewater irrigation as nitrates and other solutes may leach through the soil profile to groundwater. Furthermore, sorption, one of the potential mechanisms explaining observed high rates of SRP retention, also suggests that repeated irrigation with high concentrations of dissolved P may cause substantial P accumulation, a long-term legacy (i.e., saturation of sorption sites eventually leading to P export). Although the potential exists for adverse conditions in wastewater irrigation, proper awareness, management, and monitoring has mitigated these factors and led to successful implementation in global arid-lands.[76,84−86]

Transferability to Global Arid River Corridors. Arid-land regions are globally significant in terms of land area (over 40% of Earth's surface), population (over $^1/_3$ human population), and food production (nearly 50% of the world's livestock and cultivated land).[6] However, these regions are characterized by nutrient poor soils, high erosion rates, water scarcity, and low agricultural yields, which lead to food insecurity.[6,8,87] Additional factors such as rapid population growth and climate change place extra pressure on the FEW nexus. Based on our findings in the MRGB, direct wastewater reuse may be an effective strategy to advance the FEW nexus of arid-land regions and address these regional challenges.

For both NO_3−N and SRP export flux, arid-land basins show an increasing trend with population density, and the values reported in this study for the MRGB are comparable to those in other arid catchments (Figure 5). This behavior is supported by previous studies which have indicated that arid-land rivers are more sensitive to point sources (i.e., wastewater discharges) than rivers in humid basins. In comparison, humid basins show a more complex response to increasing population density, with a slight increase in export from low population densities to $\sim10^3$ people km^{-2}, followed by a decline in export with increasing densities.[24−27] Differing nutrient sources and responses in arid and humid basins have implications for basin-specific management of water and nutrient resources. In arid-land rivers where nutrient export is strongly influenced by point sources, direct wastewater reuse for agriculture may mitigate downstream nutrient export while beneficially reusing nutrient resources for food production. However, in order to

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provide an appreciable quantity of water and nutrients to agriculture under wastewater reuse scenarios, a sufficient population is required to generate wastewater. Previous studies of arid-land basins show that population densities span several orders of magnitude (Figure 5). In relation to the MRGB, other arid-land basins have similar or greater population densities. This suggests that there is potential to implement wastewater reuse for agriculture and achieve FEW nexus benefits in arid-lands globally. Furthermore, population growth and urbanization will increase generation of domestic wastewater, consequently increasing point source nutrient loads along populated arid river corridors.[88,89] In places where agriculture acts as a nutrient sink, wastewater irrigation can provide a holistic solution to address challenges related to urban nutrient pollution and agricultural production.

Mechanisms controlling nutrient retention in the MRGB have been observed in other arid-land rivers. Low nutrient export has been observed in the Amu Darya River of central Asia, the Ebro River of Spain, and the Gila River of the Southwestern U.S. The semiarid Amu Darya River irrigates over 3.6 million hectares of agricultural land and lies within Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, and Afghanistan. The recirculation of irrigation water within the Amu Darya irrigation network explained observed decreases in N export from the basin despite increases in N inputs (increased fertilizer application) over a 40 year period.[34] Similarly, the Ebro basin receives high N loading from fertilizers, however, the high density of irrigation channels and reservoirs in the Ebro irrigation network contribute to high retention (91% of N inputs) within the basin.[31] In the Gila River of the Central Arizona-Phoenix ecosystem, high rates of N and P retention have also been reported.[90,91] Nutrient retention in this system is strongly influenced by water conservation practices that recycle wastewater effluent for agricultural reuse and aquifer recharge. Further, high rates of inorganic N retention have also been observed in several large arid-land basins including the Murray-Darling, Nile, and Orange River basins.[24,35] Extensive agricultural development has occurred adjacent to each of these arid-land rivers and may explain the low nutrient export. The Murray-Darling Basin (MDB) is the largest and most productive agricultural region in Australia.[92] Similarly, 90% of the Nile Delta is under cultivation and is one of the most agriculturally productive areas in Egypt.[93] The arid portion of the lower Orange River supports ~71 000 ha of irrigated agricultural production.[94] The irrigated portion of each of these systems contains an extensive network of ditches and drains that supply water to fields and drain excess water back into the river, preventing soils from salinizing. The MDB contains over 6000 km of irrigation drains, which have been shown to be a potential sink for nutrients.[95] After the closure of the Aswan High Dam, over 13 000 km of irrigation drains were constructed in the Nile Delta.[96] An extensive network of irrigation ditches has been constructed along the Orange River to connect the numerous impoundments to irrigated farmland.[97] Although a range of irrigation practices is used in each of the three systems, some form of flood irrigation is common in each system.[97−100] While observed nutrient retention is high within these arid basins, nutrients are not intentionally managed for agricultural benefits. Hence, potential exists to maximize trade-offs related to nutrient cycles and the FEW nexus of global arid-lands.

Overcoming impending resource challenges in the FEW nexus is not likely to be met by a singular, all-encompassing approach or technological development. Rather, advancing the FEW nexus will require strategies tailored to the conditions and needs at local and regional scales. Using the MRGB, we identify direct wastewater reuse as a strategy to advance the local FEW nexus of an arid-land river basin with potential transferability to arid-land regions globally. Future work is needed to understand and address local factors and constraints to wastewater-nutrient reuse in the MRGB and to dynamically model trade-offs between agricultural producers, wastewater managers, and the environment to optimize nexus performance. Beyond wastewater reuse, additional research is also needed to understand how to effectively recycle other alternative, renewable nutrient sources (i.e., livestock and food wastes) to completely close the nutrient loop between food production and consumption.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b01351.

Tables showing results of the aquatic nutrient budget analyses (NO_3−N, SRP, NH_4−N) and wastewater nutrient loading (PDF)

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Notes

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