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Geospatial analysis of potential water use, water stress, and eutrophication impacts from US dairy production

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ABSTRACT

Water resource impacts from US dairy production include water use (scarcity impacts) and water quality (eutrophication impacts). These impacts are location-specific, depending upon characteristics of the region and watershed where on-farm dairy and feed production occurs. The objectives of this analysis were to evaluate the impact of US on-farm dairy production on water scarcity across the US, and evaluate dairy production's impact on eutrophication processes within watersheds as well as on the Gulf of Mexico hypoxic zone. The primary water-utilization challenge for dairy producers is irrigation for growing feed rather than on-farm use. Most dairy production in the US does not occur in water stressed areas with the exception of production in some western states. The potential impacts on local (P pollution) and regional (N pollution to the Gulf of Mexico) watershed eutrophication are more likely to occur from feed production than from on-farm dairy activities.

1. Introduction

Water-related impacts are particularly sensitive to spatial variability. Water scarcity is by its nature a local phenomenon; thus, the impact of water use will also be local (Matlock et al., 1999). Similarly, water quality impacts have significant local implications, though they can be cumulative under certain circumstances. Therefore, the impacts of dairy production on water resources and quality are dependent on the location of the production facility (Matlock et al., 1999). Conventional life cycle assessment does not explicitly consider spatial variables in the inventory or impact assessment process (Reap, Roman, Duncan, & Bras, 2008). A geospatial assessment is necessary to evaluate these impacts.

1.1. Water resources management

Water resource demand in a region is generally characterized by the drainage area (Gleick, 1996). Water resources include surface water (streams, rivers, lakes, and reservoirs) and groundwater (riparian and geologic). Most hydrologic characteristics (timing and magnitude of water availability) that define water resources are contained geographically within a drainage area; the exception is geologic groundwater. Geologic groundwater includes water from geologic strata that are not directly connected to a water body. Riparian groundwater resources are those that are directly connected to a stream, river, or lake through a saturated subsurface conveyance.

Management from the watershed level allows the manager and ecological engineer to consider factors beyond chemical pollution in protecting water quality, including habitat destruction, geomorphologic changes, and changes in land use (Ludwig, Matlock, Haggard, Matlock, & Cummings, 2008; Matlock et al., 1994). For programmatic proposes and uniformity, watersheds are often delimited by government agencies. In the United States, the Natural Resources Conservation Service and the United States Geological Survey (USGS) delineate watersheds in a hierarchical scheme with sub-watersheds nested inside watersheds inside larger drainage basins. These delineations are referred to as hydrologic units, and each is identified by a hydrologic unit code (HUC). Data are available from many government databases describing HUC areas (www.nationalatlas.gov). In the US, there are six levels of delineation, with smaller HUCs nested within larger units (Watermolen, 2006). In order of descending area, the HUCs divide the country into 21 hydrologic regions, 222 sub-regions, 352 accounting units,

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and 2150 cataloging units. Parts of the country are further delineated into watersheds and sub-watersheds.

A hydrologic region is defined by a two-digit HUC and may be the drainage basin of a major river, like the Upper Mississippi, or the combined drainage area of several rivers, such as New England. Hydrologic sub-regions divide regions and include the area drained by a river system, a section of a river and its tributaries in that reach, a closed basin or basins, or a group of streams forming a coastal drainage area (Watermolen, 2006). Sub-regions are defined by a four-digit HUC. The first two digits are the same as the larger regional HUC, and the last two define the sub-region. Accounting units, or basins, subdivide the sub-regions. They are used by the USGS for managing national water data (Watermolen, 2006). Accounting regions are defined by a six-digit HUC. The last two digits of the HUC are the accounting unit; the preceding digits describe the region and sub-region. The most common scale for water resource analysis, and the scale used in this project, is the hydrologic accounting region (HAR, or six-digit HUC).

1.2. Water supply stress index (WaSSI)

Approximately 70% of the world's freshwater withdrawals are for agricultural use (irrigation and livestock) (FAO, 2010). There are other competing demands for water resources locally and regionally. These include commercial, domestic, industrial, mining, and thermoelectric uses. Understanding the current and potential future demand for water across each demand sector is critical for anticipating stress caused by shortages. Numerous strategies for analyzing water stress have been developed. The common approach to analyzing water stress is to divide demand by availability (Sun, McNulty, Moore Myers, & Cohen, 2008). The resulting index is a measure of the proportion of water resources that have been allocated or are being used relative to the availability of water resources. For this project the Water Supply Stress Index (WaSSI) developed by Sun et al. (2008) was selected, as it provides high geographic resolution for the United States.

1.3. Eutrophication

Eutrophication is the process of water quality degradation associated with nutrient pollution to a water body (Matlock, Matlock, Storm, Smolen, & Henley, 1998; Sharpley, Kleinman, McDowell, Gitau, & Bryant, 2002). Nutrient pollution can come from agricultural, industrial, and municipal sources. Agricultural nutrient pollution generally comes from field and farm runoff, and thus is considered a non-point source load. Dairies with herd sizes greater than 700 mature dairy cows or 1000 total head (federal mandated minimum) are required to have National Pollutant Discharge Elimination System (NPDES) permits under the Clean Water Act for discrete discharges, mostly from animal waste treatment systems. State agency regulations can be more strict than federal rules. Municipal and industrial nutrient pollution is generally limited to point source discharges, permitted under the NPDES program. Industries can have non-point loads from storm water runoff, but these are increasingly regulated under the NPDES permit program. These loads can vary widely, depending on the history, size, and location of the discharge facilities. Non-point source loads are driven by rainfall and runoff events, while point source loads are often continuous discharges. Determining the allocation of the proportional impact of point and non-point source nutrient loads is very complex. The degree of eutrophication from those nutrient loads depends on a variety of local variables, including other sources of nutrients, sensitivity of the aquatic ecosystem to nutrients, and other impacts on streams such as riparian zone destruction and hydrologic regime alteration (Matlock et al., 1998).

1.4. Objectives

The purpose of this study was to analyze the impact of dairy production in the United States on water resources and eutrophication due to location of production activities. Because the determination of background agricultural impacts in individual watersheds is based on measured data and not attributed to specific sources, this is a semi-quantitative analysis of relative impacts on a regional basis. Because of the large uncertainties associated with much of the data the absolute values of water use and nutrient loss should be viewed with the appropriate understanding that they are approximations made for comparisons at large spatial scales. This analysis includes qualitative assessments of direct water use by dairy production facilities, water stress associated with dairy production, and eutrophication potential resulting from direct and indirect activities of dairy producers. The objectives were to evaluate the relative impact of US dairy production on water scarcity within watersheds across the US, to evaluate the potential for US dairy production to contribute to eutrophication processes within watersheds, and to evaluate the relative impact of US dairy production in the Mississippi River Basin on the Gulf of Mexico hypoxic zone.

2. Approach and methods

The approach used to determine the qualitative potential impact of dairy production in the US on water resources, water stress, and eutrophication is described in this section. The common strategies were to develop an inventory of input data by HAR and calculate impact using a process-based analysis. Dairy production water resource impacts were aggregated to HAR scale using an area-weighted average approach.

2.1. Watershed boundary dataset

The Watershed Boundary Dataset (WBD), defined by the USGS as "a complete digital hydrologic unit national boundary layer compiled at the sub-watershed (12-digit) level", was used to define HARs for this analysis. According to the metadata "the data consists of geo-referenced digital data and associated attributes created in accordance with the FGDC (Federal Geographic Data Committee) Proposal, Version 1.0 – Federal Standards For Delineation of Hydrologic Unit Boundaries 3/01/02". Polygons in the dataset contain unique codes for identifying watersheds and their derivatives. This dataset was developed by National Resource Conservation Services "for water-resource management and planning activities, particularly for site-specific and localized studies requiring a level of detail provided by large-scale map information." (USDA, 2011a). The six digit HUCs were used as the geographical computational elements for this assessment.

2.2. Water resources

The USGS provides water supply and use for the US within HARs every five years (Kenny et al., 2009). This dataset provides values for water use in millions of gallons per day (MGD) at the eight-digit HUC level and subdivided into eight separate sectors including irrigation and livestock. The 2005 estimates (Kenny et al., 2009) were aggregated to the six digit level and converted to million cubic meters (Mm^3) per day for use in this analysis (Fig. 1).

2.3. United States department of agriculture (USDA) census of agriculture

The Census of Agriculture is described by the USDA as "the leading source of facts and figures about American agriculture. Conducted every five years, the Census provides a detailed picture

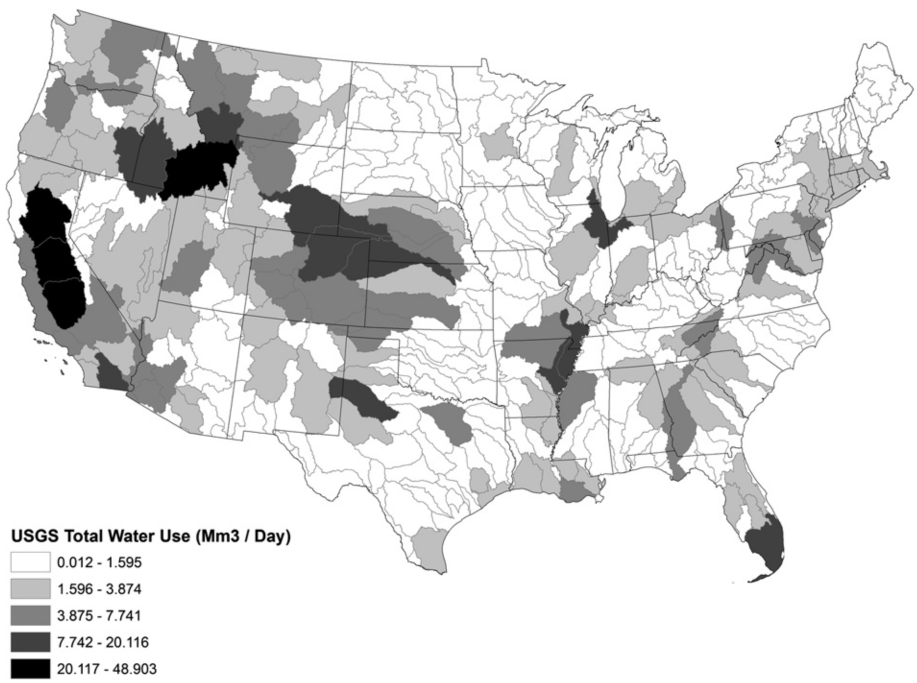

Fig. 1. United States hydrologic accounting regions with USGS estimated total water use (Mm^3 per Day) (Data modified from: Kenny et al., 2009).

of US farms and ranches and the people who operate them. It is the only source of uniform, comprehensive agricultural data for every state and county in the United States." (USDA, 2011b). Dairy cattle are differentiated from beef cattle in the report. The 2002 year data from the 2007 Census of Agriculture was used to estimate dairy cow density and corn grain and silage production at county levels in the US (USDA, 2009a). The 2002 year data was used to more closely match other datasets in the analysis which ranged from 1992 to 2005. County geospatial files were obtained from United States Census files (U.S. Census Bureau, 2002).

2.3.1. Allocation of dairy cows to watershed boundaries

In order to report dairy cattle contributions to processes within HARs, data were aggregated from county to HAR using an area-weighted approach (Fig. 2). Dairy cattle population at the county level was extracted from the 2007 Census of Agriculture (USDA, 2009a). In counties where the total number of milk cows was below a certain threshold, the USDA did not report the number of milk cows per farm to preserve the privacy of the producer. In these cases, the number of milk cows per farm was estimated using the state average of milk cows per farm. Estimates were

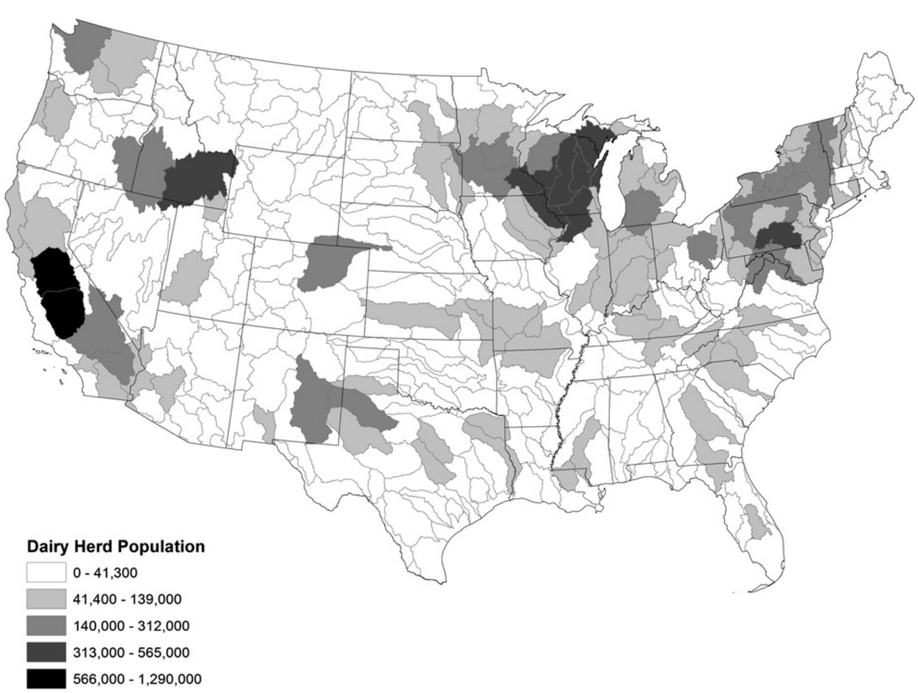

Fig. 2. United States hydrologic accounting regions with dairy herd population (Data modified from: USDA, 2009a, 2009b).

required in approximately 5% of the counties throughout the study area. Dairy cow populations for each HAR were calculated using an area weighted approach where an even distribution of dairy population was assumed across each county (head per unit area). For each HAR, the area of each county within the HAR was calculated and multiplied by the dairy cow density (head per unit area) for the county. The resulting values were then summed for the HAR to determine the total dairy cow population. These values included only first-calf heifers, mature cows, and dry cows. According to USDA herd demographic estimates this accounts for only 51.92% of the actual dairy herd, which includes bulls, calves, and un-bred heifers. To account for this, the population in each HAR was divided by 0.5192 to determine a total dairy herd final value.

2.3.2. Calculation of annual water use by dairy operations per HAR

Annual water use by dairy production facilities was calculated using an annual water use rate of 42 m^3 per year per head. This was applied to the entire herd, not just milking cows. The value of 42 m^3 per year per head was determined by using estimated average consumption of water by dairy herd demographic groups. This value was arrived at using the following method which takes into account differences in consumption values between different life and production stages of the dairy herd population. The average demographic group consumption values were multiplied by the total population of the demographic group then summed across the groups to find the total consumption value. This value was doubled to account for non-consumptive uses of water in production (flush, wash, etc.) then divided by the total herd population to obtain average herd water use per head. Many detailed variables such as heat stress were not considered due to lack of data. This was conducted on population values for five separate regions, and the average of these five regions used. Average demographic consumption values and doubling for non-consumptive uses were approximations based on values from the "Estimating Water Use for Dairy Operations" spreadsheet (Ishler, 2011).

2.4. The water supply stress index (WaSSI)

Anthropogenic (human-derived) water supplies are those that are managed and used to support human activities. These are differentiated from environmental water supplies, which support ecosystem services and functions. McNulty, Sun, Cohen, and Moore Myers (2007) and Sun et al. (2008) developed the Water Supply Stress Index (WaSSI) to quantitatively assess the relative magnitude of anthropogenic and environmental water supply and demand (Eq. (1)):

$$\mathrm{WaSSI}_x = \mathrm{WD}_x/\mathrm{WS}_x \tag{1}$$

where WD_x is water demand from anthropogenic sector x, and WS_x is water supply from anthropogenic and/or environmental sector x. The WaSSI can be used to determine current, historic, and future water supply and/or demand from environmental and anthropogenic sectors. Water demand and supply has been calculated for each 8-digit HUC watershed in the United States (Sun et al., 2008). The WaSSI model was used to determine the water stress index for HARs as defined in this study (Fig. 3). The initial analysis by Sun et al. (2008) was performed at the eight digit HUC level. These analyses were aggregated to the six digit HUC level HAR and reanalyzed from data provided by the developers of the WaSSI model (G. Sun and S. McNulty, personal communications, July, 2010). WaSSI is unique from other water availability measurement tools in that it factors in anthropogenic water demand. Therefore, it is possible to have areas with high annual levels of precipitation to have a high WaSSI value. Though unique, it is basic in principle and is similar to most current strategies to measure water stress by using a ratio of demand to supply. The transition to water stress occurs at 0.2 and from stress to scarce at 0.4.

Sun et al. (2008) analyzed scenarios for water supply stress in the US using two climate change models. Both climate projections were derived from transient global climate models and are widely used by the climate change research community (McNulty et al., 2007). The Hadley Climate Scenario Model (HadCM2Sul)

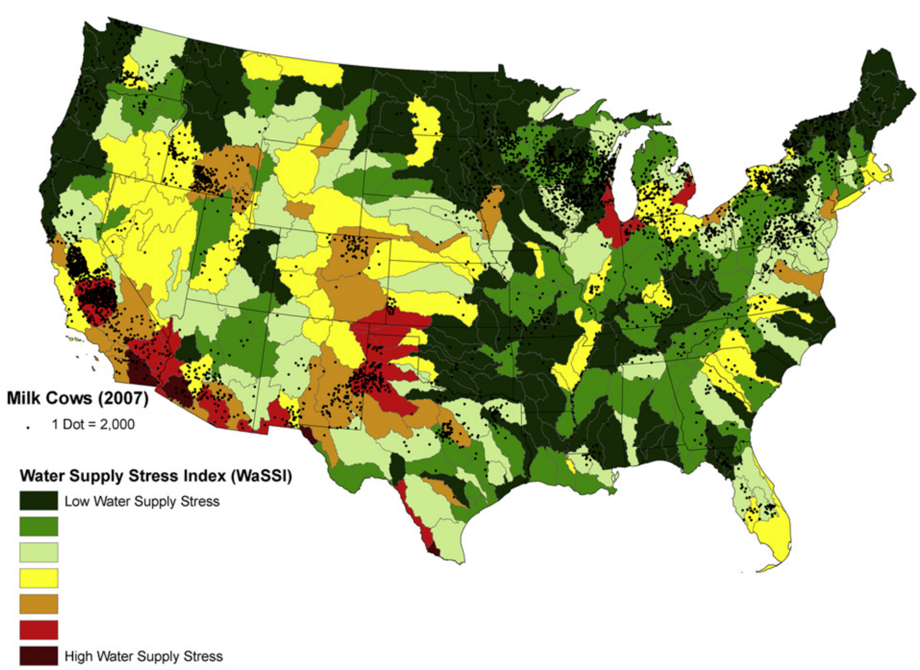

Fig. 3. Water Supply Stress Index (WaSSI) for hydrologic accounting regions, with dairy production density represented by randomly located dots (one dot equals 2,000 head of dairy cows in that HAR) (Data modified from: Sun et al., 2008 and USDA, 2009a, 2009b).

predicted that by 2020, the region east of the Mississippi River will experience up to 20% increase in annual precipitation when compared with the average historic climate (1985–1993). The Hadley model predicted that areas west of the Mississippi River will experience a decrease in annual precipitation of up to 10% and an increase in air temperature (>0.5 °C). In contrast, the Climate and Global Change General Circulation Model (CGC1) predicts that most of the southern US will have a 10% decrease in annual precipitation and a larger increase in average annual air temperature in northern parts of the country by 2020. The impact of both model scenarios and increasing urban demand were simulated in this analysis to determine potential increases in water scarcity in important dairy regions.

2.5. Eutrophication

Eutrophication is the direct result of nutrient loads to water bodies (Sharpley et al., 2002). As indicated previously, the impact of nutrient loads is both local and regional; phosphorus (P) loads influence eutrophication in freshwater systems (Ludwig et al., 2008), while nitrogen (N) loads influence eutrophication in estuaries like the Gulf of Mexico (Sharpley et al., 2002). Estimating the impact of dairy farms on eutrophication required an inventory of nutrient sources and impact assessment for nutrient loads. Nutrient loads were estimated from relative N and P loads at two scales: 1) the HAR level and 2) the Mississippi River Basin (MRB). The impact of those loads was qualitatively evaluated by calculating the relative amount of N and P delivered from each HAR to the Mississippi River estuary, where the presumed impact was manifested in low oxygen in the Gulf of Mexico.

2.5.1. Estimation of nutrient loads for each HAR using SPARROW

The results of a 2008 USGS study utilizing the SPARROW (SPAtially Referenced Regressions On Watershed Attributes) model were used to characterize spatial and categorical sources of N and P from HARs within the Mississippi River Basin (Alexander et al., 2008). SPARROW is a watershed modeling technique based on a hybrid statistical and process-based approach to estimate sources and contaminant transport in watersheds and surface waters (Schwarz, Hoos, Alexander, & Smith, 2006). The method was designed to reduce the problems of data interpretation caused by sparse sampling, network bias, and basin heterogeneity (Smith, Schwarz, & Alexander, 1997). Statistically based relations between stream-water quality and environmental factors such as contaminant sources, land-surface characteristics, and in-stream contaminant losses were considered (Schwarz, Smith, Alexander, & Gray, 2005). The Alexander et al. (2008) study standardized loads to 1992 land use conditions and mean annual flow from the period of 1975–2000. Accuracy of the model for unmonitored reaches was given as 55–76% of the mean value. This represented higher accuracy than previous SPARROW models, and makes this dataset the best available for large scale comparative analysis. Loads were aggregated to the HAR level through summation of the loads for each 8 digit HUC. This analysis was limited to the Mississippi River Basin because this was the only basin with SPARROW modeling completed. SPARROW models are currently being developed for all regions in the US except California and the US Southwest. These should be completed by the end of 2012, and will support a more comprehensive analysis.

2.5.2. Estimation of dairy production contribution of nutrient loads at the HAR scale

The proportion of nutrient loads from each HAR attributable to dairy production was estimated by making a series of broad assumptions about agricultural non-point source loads of N and P. Incremental dairy loads at the HAR scale were estimated using the amount of nutrients (N and P) excreted by an average animal each year multiplied by the number of animals in each HAR. Manure nutrient excretion values were obtained from USDA research (Gollehon et al., 2001). Nitrogen from cows in confined management operations was multiplied by 0.4 to account for manure management reductions, and all manure nutrients were multiplied by to 0.1 as the land-applied runoff coefficient. The value of 0.4 came from the ratio of excreted N to available N in the Gollehon et al. (2001) dataset. The value of 0.1 was an average estimate from the wide range of potential nutrient transport values, which can range from 0 to 0.9 (Johnes, 1996), and the necessity of simplicity in calculations in this screening analysis. While this may be a low estimate in some instances, the streamlined nature of this analysis provides comparative utility despite the absence of site-specific fate and transport analysis.

2.5.3. Estimation of nutrient loads from each HAR from corn grain and silage

The inventory of nutrients from feed (predominantly corn and silage) were estimated by multiplying the bushels of corn and silage produced in each HAR by the application rate per bushel and assuming a field loss rate of 10%. Corn grain and silage yields were adjusted to the HARs from county level data (USDA, 2009a). Crop yields (m^3 for corn and kg for silage) for each HAR were calculated using an area weighted approach, where an even distribution of total corn or silage production was assumed across each county (m^3 or kg per unit area). For each HAR, the area of each county within the HAR was calculated and multiplied by the crop production density (m^3 or kg per unit area) for the county. The resulting values were then summed for the HAR to determine the total crop production (m^3 or kg). The fertilizer application rates assumed for corn were 38 kg N per m^3 per hectare and 11 kg P per m^3 per hectare (1.2 and 0.34 pounds N and P respectively per bushel corn yield per acre). The fertilizer application rates assumed for silage were 0.01 kg N per kg per hectare and 0.003 kg P per kg per hectare (10.4 and 3.0 pounds N and P respectively per ton silage yield per acre). These nutrient application rates were developed as national averages from reported rates of application (Brown, Hart, Horneck, & Moore, 2010; Dahnke, Fanning, & Cattanach, 1992; Davis & Westfall, 2009). Spatial allocation of corn grain and corn silage used for dairy feed was beyond the scope of this analysis. Estimates of the percent of corn grain and silage use for feed by dairy production based on average national dairy feed rations (Thoma et al., 2013), as well as national level data on milk production and crop production (USDA, 2009b), were approximately 4% of corn grain and approximately 55% of corn silage. However, given the complex nature of corn distribution, geographic correlation between corn producing watershed and dairy use of corn and silage for feed was not possible with this analysis. Therefore results of this crop analysis are presented as total loads even though dairy use only constitutes 4% of corn grain and 55% of corn silage production on an annual basis.

2.5.4. Estimation of nutrient loads delivered from each HAR to the Gulf of Mexico

Only a portion of the nutrients that leave each HAR reach the Gulf of Mexico. Nutrients continue to cycle in the aquatic environment and can be deposited in sediments (Chaubey, Sahoo, Haggard, Matlock, & Costello, 2007; Ludwig et al., 2008; Matlock et al., 1998). The nutrient loads for each HAR from each source (total, dairy production, corn, and silage) were multiplied by the SPARROW Gulf Transport Ratio. This ratio was determined by dividing the delivered load by the incremental load of each nutrient from the SPARROW data (Alexander et al., 2008).

3. Results and discussion

The purpose of this analysis was to estimate the impact of dairy production in the United States on water resources and eutrophication accounting for the location of production activities. The results of this analysis are not fully quantitative; they do provide a semi-quantitative assessment of water resource impact and eutrophication impact. Dairy production is highly concentrated in a few regions, with five HARs containing the highest dairy herd density; two located in California, one in Wisconsin, one in Pennsylvania, and one in Vermont. Over half the US dairy herd is located in less than 30 HARs (Table 1). This spatial aggregation drives the outcomes of these analyses. These analyses represent indicators of vulnerability for the dairy industry to water resource stress and water quality impacts. While the authors recognize that inter-basin transfers of water occurs in many locations, this was not considered a desirable or pragmatic solution to intra-HAR scarcity due to the high transaction and implementation costs. The results of this set of analyses are presented in three sections: Water Supply and Use Estimates, The Water Supply Stress Index, and Eutrophication.

3.1. Water supply and use

Water used for agricultural purposes includes irrigation, livestock and dairy production. Irrigation use in the US in 2005 was greater than 12 Mm^3 per day in some areas of Arkansas, Mississippi, Tennessee, California, and Idaho (Fig. 4). Water use by livestock showed high density of use in central California, the Texas and Oklahoma panhandles, North Carolina, and Pennsylvania. Estimates of on-farm dairy use of water at the HAR level mirrored dairy herd density as a single per head water used value was used nationally (Fig. 5, Table 1). The proportion of dairy water use to total agricultural water use was less than 50% in all hydrologic accounting units except one very small area in northern Vermont (HAR 011100, St. Francis). Dairies used greater than 10% of total agricultural water in less than 30 HARs. While dairies in the California Central Valley have high water use values (Mm^3 per day), this was less than 4% of total agricultural water use in those HARs. Inversely, three HARs in Mississippi and Texas had low water use but represented over 25% of all agricultural water used in those HARs. This indicates that, in most areas, reduction of on-farm water use for dairy production will have little impact on the overall water stress. For situations where the feed for dairy animals is being produced in close proximity to the dairy facility, the amount of water used for irrigating crops will have a much higher impact on water stress.

3.2. The water supply stress index (WaSSI)

The WaSSI analysis (Fig. 3) represents the ratio of water demand to supply (water available for appropriation for human use) in each

Table 1
Top HARs for dairy herd population and water stress potential. Water uses other than on-farm dairy come from the USGS water use dataset (Kenny et al., 2009).

HAR name	HAR code	States	Watershed area (km^2)	WaSSI	Dairy herd population	Dairy on-farm water use (Mm^3 day^{-1})	Total water use (Mm^3 day^{-1})	Total agriculture (Mm^3 day^{-1})	Irrigation water use (Mm^3 day^{-1})
Tulare-Buena Vista Lakes	180300	CA	42,434	0.59	1,290,000	0.150	29.68	26.28	26.02
San Joaquin	180400	CA	40,839	0.19	1,090,000	0.128	25.52	21.36	21.12
Upper Snake	170402	ID MT NV UT WY	78,050	0.36	565,000	0.066	48.90	42.13	42.02
Salton Sea	181002	CA	18,820	2.53	63,700	0.007	8.58	7.30	7.27
Brazos Headwaters	120500	NMTX	37,772	0.72	184,000	0.022	8.25	8.02	7.92
Southern Mojave	181001	CA	22,781	0.66	154,000	0.018	2.30	1.14	1.11
Upper Pecos	130600	NM TX	61,165	0.39	221,000	0.026	2.33	2.13	2.07
Northern Mojave	180902	CA NV	61,954	0.39	204,000	0.024	6.61	3.24	3.20
South Platte	101900	CO NE WY	62,566	0.47	157,000	0.018	11.89	9.44	9.38
Southwestern Lake Michigan	040400	IL IN MI WI	5176	0.99	65,800	0.008	3.76	0.09	0.08
Lower Gila	150702	AZ	18,091	1.42	41,300	0.005	4.65	3.96	3.95
North western Lake Michigan	040301	MI WI	31,924	0.15	380,000	0.044	1.10	0.08	0.04
Southeastern Lake Michigan	040500	IN MI	33,385	0.16	303,000	0.035	2.83	0.96	0.92
Lower Susquehanna	020503	MD PA	23,849	0.09	527,000	0.061	2.53	0.14	0.03
Upper Illinois	071200	IL IN MI WI	28,242	0.60	80,700	0.009	9.50	0.45	0.42
Middle Brazos-Bosque	120602	TX	18,970	0.35	133,000	0.015	0.48	0.13	0.08
Lower Colorado	150301	AZ CA NV	30,432	0.87	52,400	0.006	5.36	4.67	4.65
Prairie Dog Town Fork Red	111201	NM OK TX	19,971	0.72	54,400	0.006	3.14	2.99	2.90
Potomac	020700	MD PA VA WV	38,056	0.13	289,000	0.034	3.98	0.13	0.06
Upper Mississippi-Maquoketa-Plum	070600	IA IL MN WI	22,211	0.11	347,000	0.040	0.47	0.12	0.03
Upper Mississippi - Black-Root	070400	IA MN WI	27,843	0.07	497,000	0.058	0.88	0.21	0.14
Middle Snake-Boise	170501	ID NV OR	85,234	0.19	174,000	0.020	20.12	18.64	18.59
Western Lake Erie	041000	IN MI OH	31,026	0.23	139,000	0.016	2.18	0.09	0.06
Lower Gila-Aqua Fria	150701	AZ	20,391	0.23	139,000	0.016	4.43	2.71	2.70
Southwestern Lake Ontario	041300	NY PA	9244	0.19	155,000	0.018	0.57	0.04	0.03
Eastern Lake Erie	041201	NY OH PA	7659	0.21	131,000	0.015	1.07	0.03	0.02
St. CI air-Detroit	040900	MI	10,235	0.78	30,400	0.004	3.72	0.05	0.05
Fox	040302	WI	16,537	0.06	349,000	0.041	1.28	0.42	0.38
Muskingum	050400	OH	20,819	0.10	210,000	0.024	0.84	0.04	0.01
Oswego	041402	NY	13,067	0.10	213,000	0.025	0.84	0.04	0.02

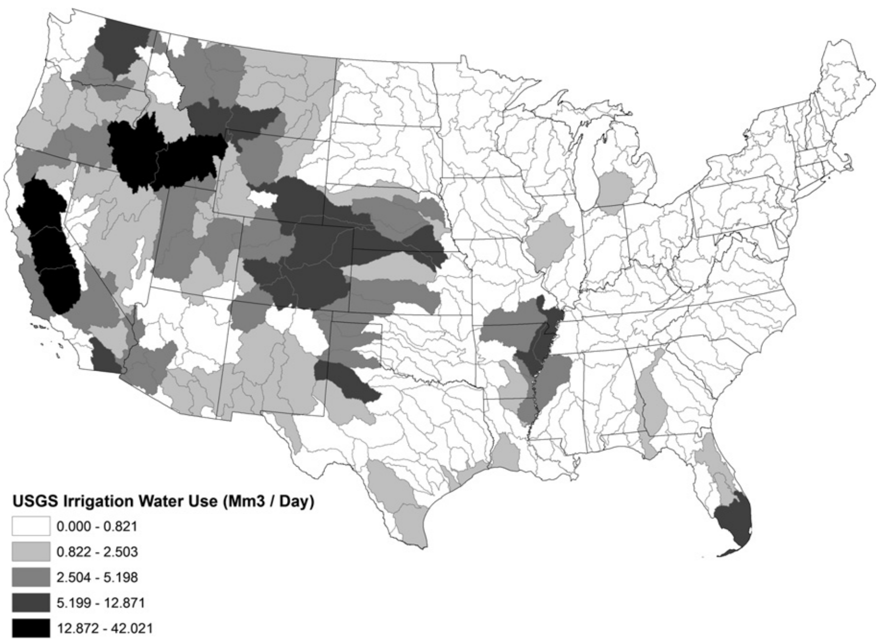

Fig. 4. United States hydrologic accounting regions with USGS estimates of water use by crop irrigation (Mm^3 per day) in 2005 (Data modified from: Kenny et al., 2009).

HAR in the US. The green HARs have water demands less than 20% of supply on an annual basis. The yellow and orange HARs have water demands between 20 and 40% of supply. The red HARs show areas where water demand exceeds 40% of supply on an annual basis. For the most part, the results are consistent with common understanding of water scarcity in the US. However, the region of high water stress around Lake Michigan (Wisconsin, Illinois, and Indiana) was unexpected. This area has dense urban land use with high municipal and industrial demand. The proximity to Lake Michigan suggests that water stress in this region is the result of lagging infrastructure or model methodology constraints (such as interbasin transfer), and is not water resource driven. The high stress in the James River Basin in Virginia was also unexpected. This area is also urbanizing rapidly. The competing demand for water resources from urban use (industrial, municipal, thermo-electric) will increase in regions with increasing urban population.

3.3. Eutrophication

The impact of dairy production on nutrient loading and eutrophication at local and regional scales is the result of the density within HARs of dairy herd, crop production, and proximity to the

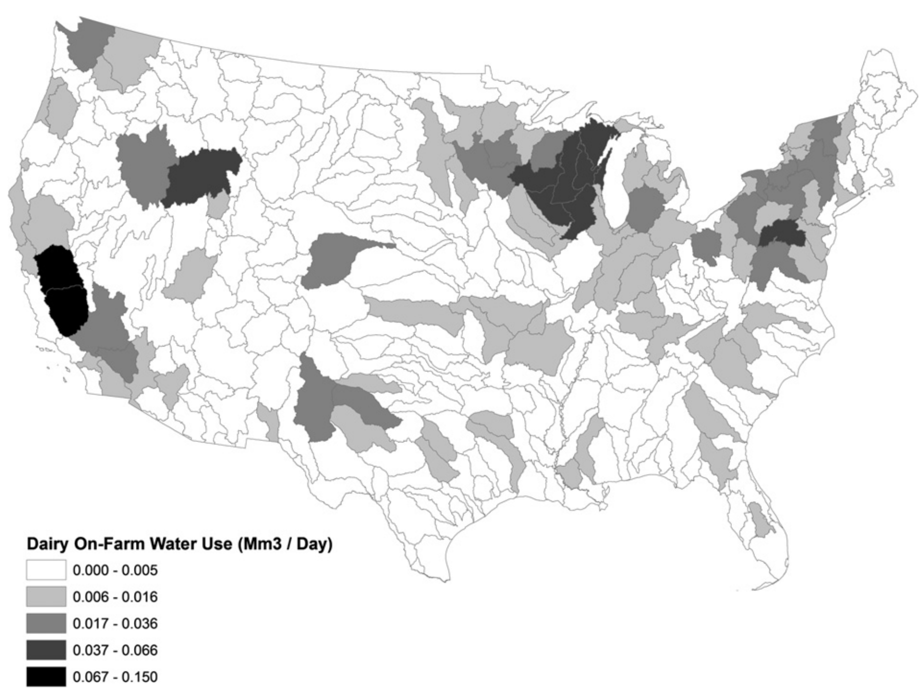

Fig. 5. United States hydrologic accounting regions with dairy production on farm water use (Mm^3 per day).

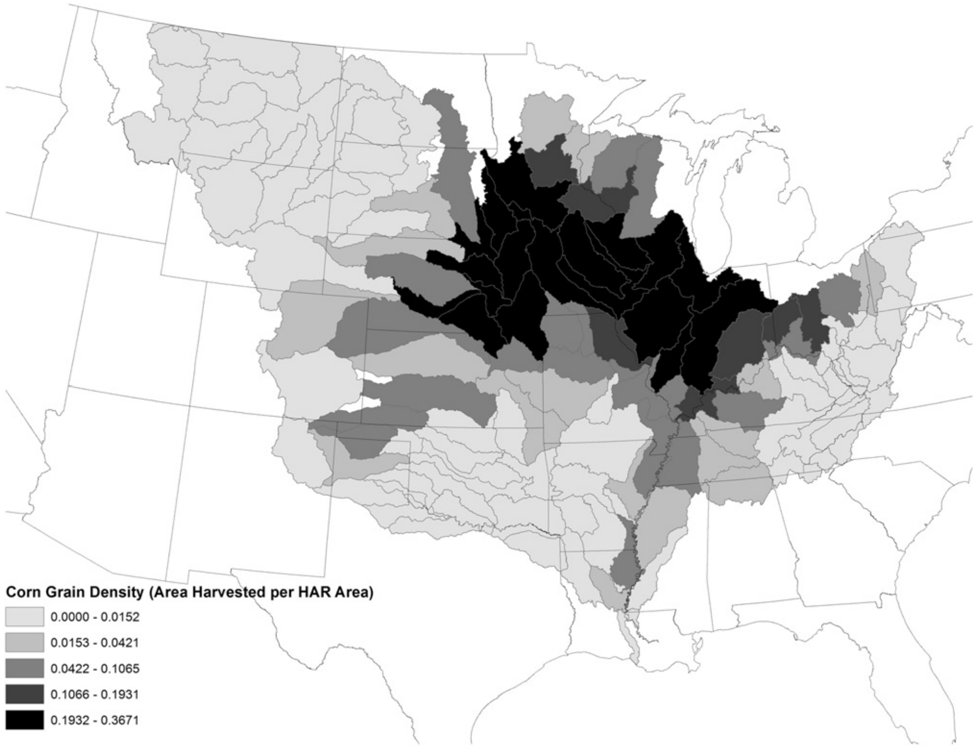

Fig. 6. Mississippi River Basin hydrologic accounting regions with corn grain production area ratio.

Gulf of Mexico, among other things. Dairy herds in the Mississippi River Basin are most densely concentrated in the Great Lake states (Minnesota, Wisconsin, and Illinois) and Iowa, with some high density in Ohio. Corn production is most dense across this northern region, commonly referred to as the Corn Belt (Fig. 6). More than 20 HARs had greater than 20% of their area in corn production, with some greater than 30%. Silage production was shifted west into the Dakotas, Nebraska, and Kansas (Fig. 7). The highest proportional area for silage production within an HAR was less than 3%. While these numbers are low, much of the silage produced in these HARs

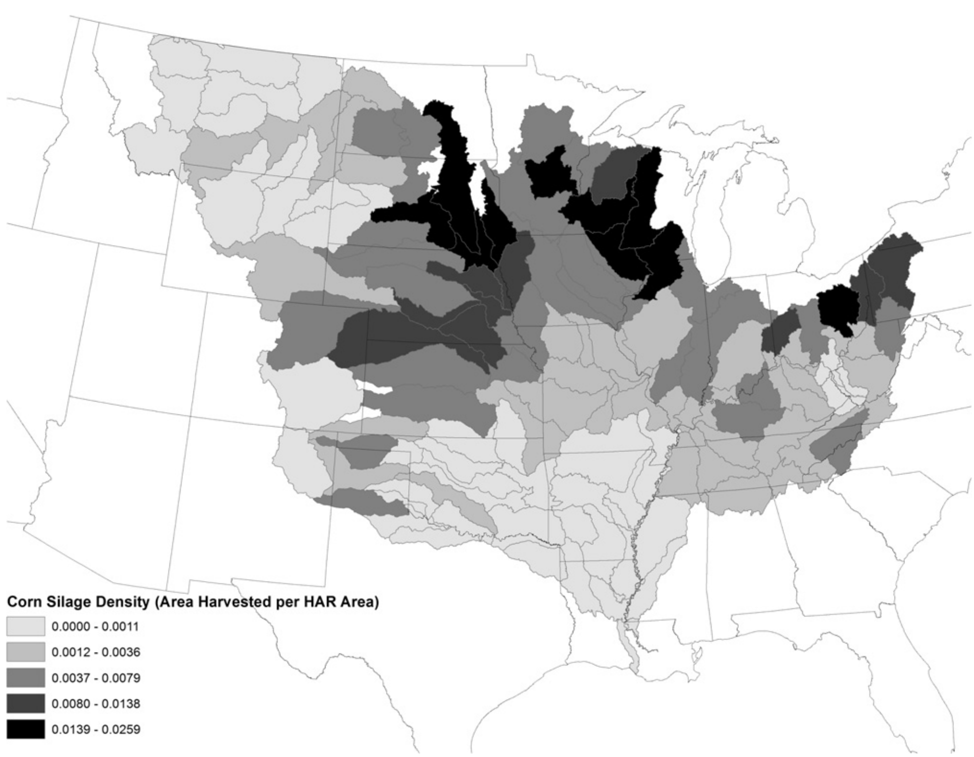

Fig. 7. Mississippi River Basin hydrologic accounting regions with corn silage production area ratio.

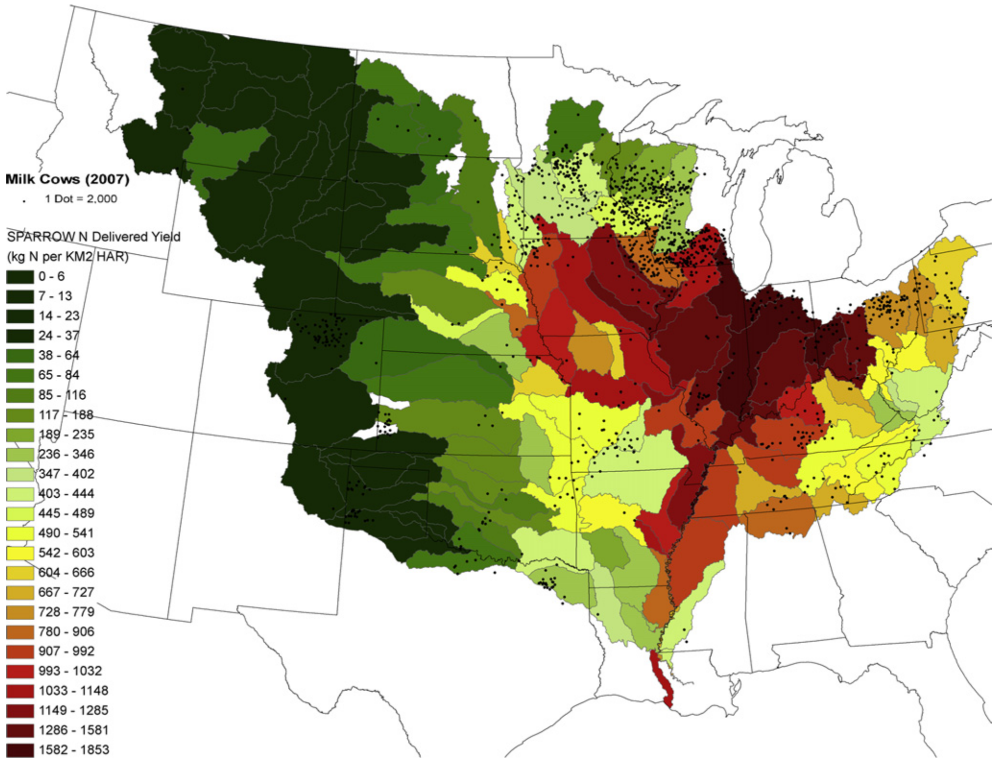

Fig. 8. SPARROW model nitrogen delivered annual yield (kg N per km^2) to the Gulf of Mexico from the Mississippi River Basin, with dairy herd population indicated by dots (one dot = 2000 head).

goes to feed dairy cattle, while only a small fraction of the corn produced is destined to be dairy feed. Thus the relative impact of dairy corn silage on local and regional nutrient loads is not insignificant.

3.3.1. *Local eutrophication impacts*

Incremental yield of nutrients from each HAR indicated the potential eutrophication impact on local water bodies. The SPARROW model result for N yield (kg N per km^2 HAR) indicated that

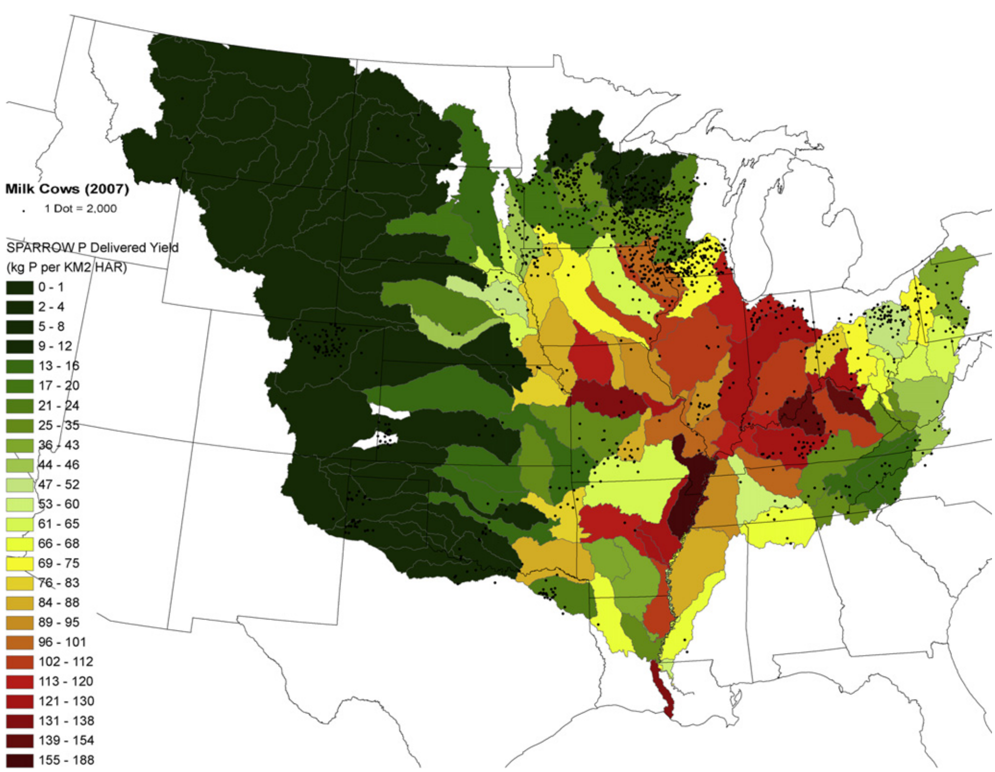

Fig. 9. SPARROW model phosphorus delivered annual yield (kg P per km^2) to the Gulf of Mexico from the Mississippi River Basin, with dairy herd population indicated by dots (one dot = 2000 head).

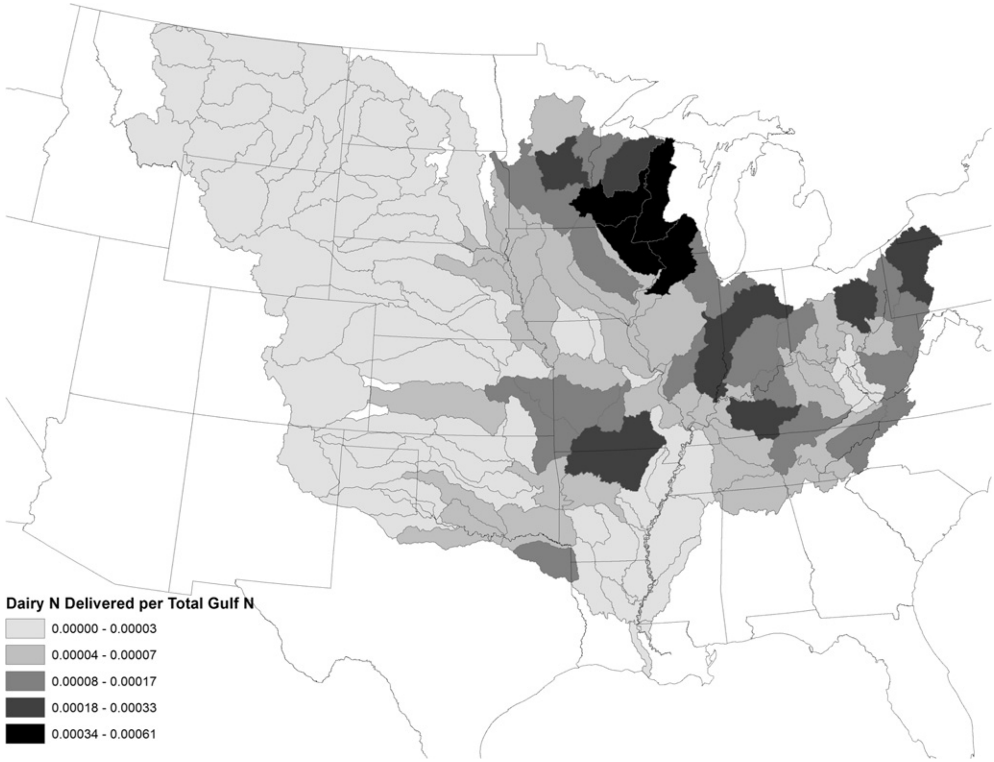

Fig. 10. Ratio of on farm dairy production nitrogen load delivered to the Gulf of Mexico to total nitrogen load from SPARROW model.

most of the highest yielding HARs were proximal to the Mississippi, Missouri, and Ohio Rivers, and were in the high density corn HARs. Phosphorus rather than N is generally the limiting nutrient in freshwater systems (Chaubey et al., 2007; Matlock et al., 1998, 1999; Sharpley et al., 2002). Incremental P yields (kg P per km^2 HAR) were much more distributed across the Mississippi River Basin. Phosphorus is transported predominantly through attachment to eroded soils (Chaubey et al., 2007; Matlock et al., 1999; Sharpley

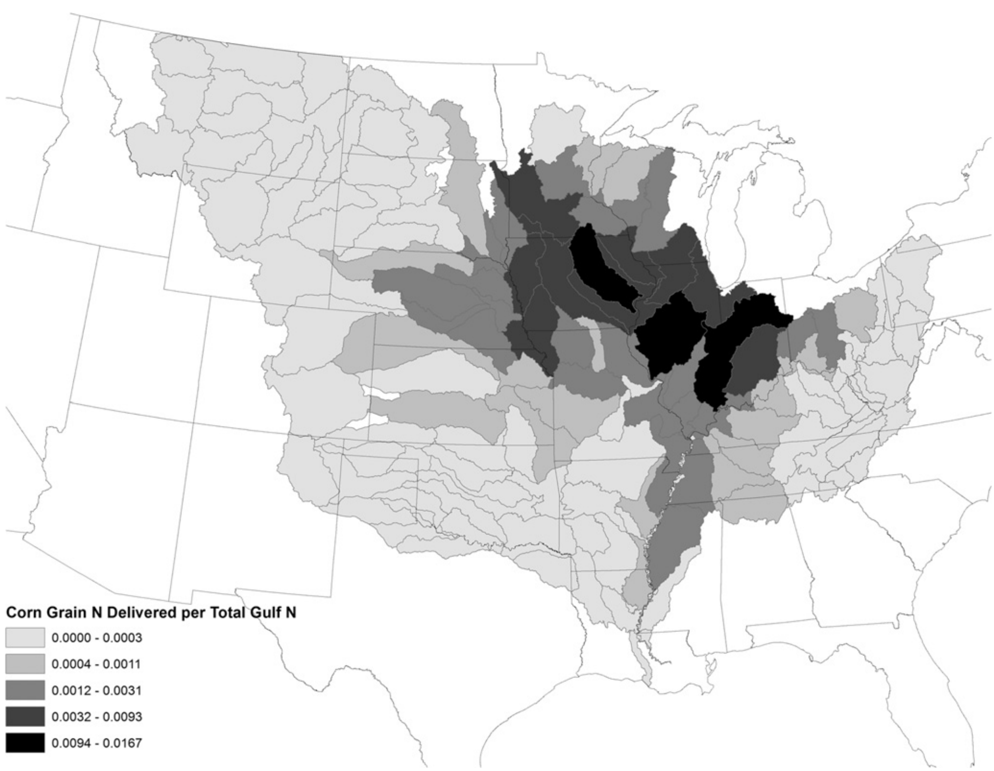

Fig. 11. Ratio of corn grain production nitrogen load delivered to the Gulf of Mexico to total nitrogen load from SPARROW model.

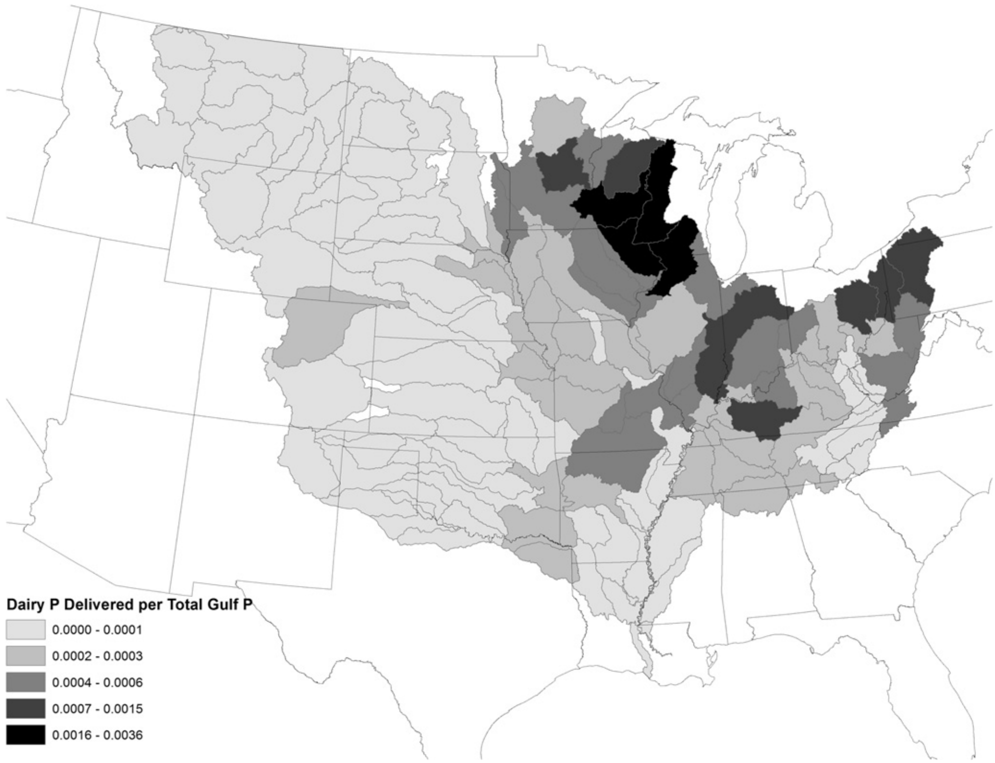

Fig. 12. Ratio of on farm dairy production phosphorous load delivered to the Gulf of Mexico to total phosphorous load from SPARROW model.

et al., 2002); clearly the P loads from HARs across the Mississippi River are not as spatially correlated to corn production as N loads. Predominant freshwater eutrophication impacts from dairy production are spatially associated with P loss in corn and corn silage production rather than dairy herd density. The HARs with the highest herd density did not have the highest incremental yields of N or P in their basins, suggesting sources other than runoff from dairy facilities as the major load source.

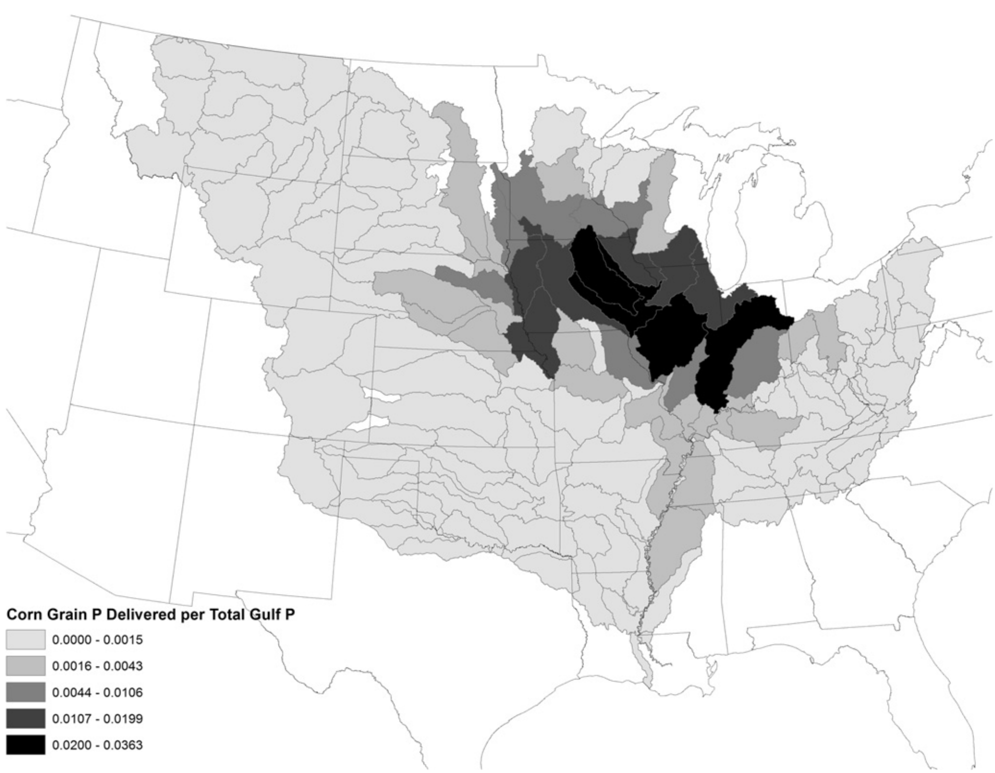

Fig. 13. Ratio of corn grain production phosphorous load delivered to the Gulf of Mexico to total phosphorous load from SPARROW model.

3.3.2. Regional eutrophication impacts

The regional eutrophication impact from dairy production is best estimated by the amount of N and P reaching the Gulf of Mexico. The SPARROW model predicted relative nutrient contributions from each HAR to Gulf loading using a statistical analysis of observed data across a broad network of monitoring stations (Fig. 8). The N delivered to the Gulf of Mexico from HARs in the Mississippi River Basin is significantly lower than the incremental yields from the HARs at the point of exit from each basin. SPARROW simulations of P yield delivered to the Gulf showed the significance of proximity to the conveyance through major rivers to move sediment and P to the Mississippi River and out to the Gulf (Fig. 9).

The results of the assessment of the impact of dairy production on nutrients delivered to the Gulf of Mexico relative to the total simulated load showed that on-farm dairy production and silage production contributed a very small fraction to the total N loads to the Gulf, while corn production contributed a significant proportion of total N loads to the Gulf. Analysis of N loads from on-farm dairy activities (primarily manure application to fields) showed the HARs with the largest loads contributed less than 0.1% of total N to the Gulf of Mexico (Fig. 10). Cumulative (from all dairies in the MRB) on-farm dairy impacts to N loading in the Gulf of Mexico were less than 3% of total loads. The HARs of highest contribution were those with highest density of herds. Corn production had the highest impact on Gulf of Mexico N loads (Fig. 11). This analysis of N loads is for total corn production. The proportion allocated to the dairy industry would be roughly the proportion of feed corn produced that is fed to dairy cattle (about 4% of corn grain, 55% of corn silage). Corn silage contributions of N loads in the Gulf of Mexico were estimated to be as much as 50 times lower than that of corn, though much of the load is attributable to dairy production since a significant portion (55%) of corn silage is fed to dairy cattle.

A different pattern was observed with the impact of dairy production on P load from HARs relative to total Gulf of Mexico P loads. Analysis of P loads from on-farm dairy activities (manure application to fields) indicated that on-farm manure management could contribute up to approximately 3% of total P to the Gulf of Mexico (Fig. 12). As with N, the HARs of highest contribution were those with the highest density of herds. Corn production showed the highest impact on Gulf of Mexico P loads (Fig. 13). This analysis of P loads is for total corn production. The proportion allocated to the dairy industry would be 4%, the proportion of total yield fed to dairy cattle. Silage contributions of P loads in the Gulf of Mexico were estimated to be as much as 30 times lower than that of corn, although most of this load is attributable to dairy production since a significant portion of silage is fed to dairy cattle, and those producers who use silage for feed are concentrated in the western region of the upper MRB. These findings suggest that dairy production would be a small but still significant contributor of nutrient loads in the Mississippi Basin.

4. Conclusions

The objective of this project was to analyze the impact of dairy production in the United States on water resources and eutrophication due to location of production activities. The approach used to determine the impact of dairy production in the US on water resources, water stress, and eutrophication incorporated consistent and, to the extent possible, unbiased assumptions. The conclusions drawn from this analysis are broad. The lack of availability of comprehensive data from contemporary analysis necessitated the use of datasets from different years. This adds to the uncertainty of the analysis since conditions of hydrology and agricultural production change on a year to year basis. Despite the inherent uncertainty of these methods, the resulting analyses are reasonable indicators of vulnerability of the US Dairy Industry to water resources stress and eutrophication potential. A more comprehensive analysis, supported by higher spatially resolved data, could provide a quantitatively rigorous assessment of these vulnerability indicators. Much of the data for this study was based on county, state, or national level ag statistics. Resolving these stats to the watershed level resulted in an analysis at the HUC6 (HAR) level. More spatially resolved data on dairy population and feed stock allocation would allow for an analysis on an 8 or 12 digit HUC level where most water resource issues are manifested. A more comprehensive analysis of the dairy production system should include identification of the geographic sources variability of feed rations so that impacts can be properly distributed, and more detailed watershed-specific input data and methods to estimate the transport of nutrients from manure application and crop fertilization. The primary transport mechanisms for N are infiltration and runoff associated with solubilization of nitrogen fertilizers in water. The primary mechanism for P transport is erosion where P is associated with soil particles.

4.1. Water supply and use estimates

Water scarcity in agricultural production is a regional phenomenon, based on climate and agricultural intensity. The majority of agricultural water use is found in crop irrigation. Current on-farm dairy production water use (Mm^3) is less than 0.5% of irrigation water use in most HARs. The challenge for dairy producers in sustainable water supply appears to be tied to irrigation for growing feed rather than on-farm use.

4.2. The water supply stress index (WaSSI)

Most dairy production in the US does not occur in water stressed areas with the exception of production in some areas of California, Arizona, New Mexico, Texas, Utah, and Idaho. The WaSSI analysis showed that competing demands for water resources, compounded with likely decreases in precipitation in the western US, could result in increased regional scarcity. The arid West will likely experience significant decreases in precipitation in the coming decades, resulting in exacerbated scarcity in California, Arizona, New Mexico, Texas, Utah, and Idaho. More significantly for US dairy production, the decrease in precipitation in the Great Plains could result in reduced yield and production of silage and corn for feed.

4.3. Eutrophication

This analysis of the impacts of dairy production on eutrophication from the Mississippi River Basin indicated that nutrients have both local and regional impacts. The predominant impacts from N were associated with corn production, and manifested at the regional (Gulf of Mexico) scale. The impacts from P on eutrophication were more complex; corn produced the largest local and regional loads to streams, resulting in local potential for eutrophication. On-farm contributions of P to local streams have the potential to increase the rate and extent of eutrophication. Where the density of dairy herds is high in a watershed this impact can be significant. However, impact on the Gulf of Mexico from dairy phosphorus is very low relative to overall P loads, and relative to stream-level impacts. These analyses are based on assumptions made regarding the aggregation and allocation of data for dairy and on the assumptions used in the SPARROW models implemented by USGS. The quantitative estimates of loads are less resilient than the relative estimates of loads from various sources. The most effective approach to reducing US dairy producers' impact on eutrophication would be to reduce N loss from corn, reduce sediment loss from fields to reduce P transport, and reduce P loss from manure application on-farm (Chaubey et al., 2007; Matlock et al., 1999; Sharpley et al., 2002).

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The funding organizations provided guidance in framing the goals of the research and developing the suite of manuscripts for submittal for publication.

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