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Spatial and Temporal Analyses of Environmental Effects on *Zizania palustris* and Its Natural Cycles

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October 2017

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GIS	geographic information system
GLIFWC	Great Lakes Indian Fish and Wildlife Commission
NLDAS	North American Land Data Assimilation System
Z. palustris	*Zizania palustris*

TECHNICAL MEMORANDUM

SPATIAL AND TEMPORAL ANALYSES OF ENVIRONMENTAL EFFECTS ON *ZIZANIA PALUSTRIS* AND ITS NATURAL CYCLES

1. INTRODUCTION

As part of a joint education and research effort funded by NASA, research studies were initiated involving students associated with the Ojibwe and researchers at Marshall Space Flight Center. Topics were chosen that satisfied the nature of the work proposed and were tractable, given the student's constraints (abilities, interests, and time). One of the studies, which spanned two summers, examined some potential environmental effects on northern wild rice in northern Wisconsin. The rice of interest is naturally occurring ('wild' wild rice), as opposed to cultivated wild rice ('paddy' wild rice).[1]

More information on the program can be found in "Gidakiimanaaniwigamig (Our Earth Lodge) STEM Camp: Investigating climate change and its effect on Ojibwe lifeways," P.I. Courtney Kowalczak, Fond Du Lac Tribal Community College, a proposal in response to NASA Program Announcement: NNH13ZHA002N-NICET-NASA Innovations in Climate Education–Tribal (NICE-T), funded by the NASA Office of Education, Integration, Minority University Research and Education Program.

1.1 Cultural Significance of Wild Rice

Zizania palustris (*Z. palustris*) (ref. 2) is known as 'maanomin' or the 'good berry' to the Ojibwe, who are part of the Anishinaabe culture. The Ojibwe people, termed Chippewa by the US government, refer to themselves as the Anishinaabe (pluralized form is Anishinaabeg). The terms Ojibwe, Chippewa, and Anishinaabe all have multiple spellings, and the referent peoples vary.

The importance of wild rice to the culture of the Ojibwe is apparent even within their migration story. According to this, they separated from the Lenni Lenape on the east coast of the continental United States when Gitchi Manitou, the Great Spirit, manifested itself as a giant turtle in a vision to a young boy, telling him to lead his people to "where the food grows on water." Along the journey, the Anishinaabe people settled along the coasts of the Great Lakes, from the western shores of the lower peninsula of present-day Michigan, to the eastern coast of Minnesota along Lake Superior. Traditionally, *Z. palustris* is referred to as an animate being, such as him/her, rather than it. Today *Z. palustris* is still a sacred grain to the Ojibwe. It also has economic importance to the tribe's members. In 2007, the rice harvest generated more than $400 thousand in income for tribal members in Minnesota.[3]

1.2 Study Rationale

While northern wild rice has been extensively studied, the bulk of the studies have been ground or laboratory based. Remote sensing and geographic information system (GIS) technology has only been used to a limited extent. For example, the authors in reference 4 used Landsat data to map the location of wild rice in north-central Minnesota. This was a classic land cover analysis—i.e., where, geographically, does the targeted species occur. Minnesota Geospatial Commons has a similar dataset on their website for the entire state. It can be found at <https://gisdata.mn.gov/dataset/env-wild-rice-lakes-rivers-wld>. The Great Lakes Indian Fish and Wildlife Commission (GLIFWC) has one that has a wealth of data, including wild rice covering Michigan, Wisconsin, and Minnesota, found at <http://maps.glifwc.org/>. Spatial analysis has also been used by authors such as Drewes and Silbernagel (ref. 5), who sought to understand wild rice harvesting in the context of the spatial landscape and across multiple governmental management systems.

However, GIS technology can be used to do more than examine where something occurs. It can also analyze relationships between any variables that are spatially co-registered. Furthermore, the analyses can be performed fairly rapidly once the necessary software is minimally mastered. Thus, the location or extent of wild rice, if known, could be evaluated against the large number of spatially mapped environmental variables stored by NASA and other organizations. As many of the available environmental variables may be affected by changing climate, such analyses could contribute directly to the goals of the funded project.

The researchers decided to test a number of environmental variables against a spatial database of wild rice, seeking potential patterns that might illuminate dependencies of wild rice on the climatic variables. Also, to a large degree, the research effort reported here was an effort to learn what the available data (which were not designed nor measured for the purposes of this study) could tell us if we listened. The analytical work was considered exploratory and of comparable importance to the educational goals.

1.3 Biology of *Zizania palustris*

The reader should note that there are two species of wild rice, *Z. palustris* and *Z. aquatica*, that grow in the same region. The differences between the rice are not significant here. Both are used by the Ojibwe in the same way, and the distinction between the species is not consistently maintained in nonspecialist literature. *Z. palustris* is an annual, subaquatic grass, active from mid-April through late August or early September in Wisconsin and Minnesota. For several reasons, the northern wild rice has been extensively studied. (See refs. 6–15 for a 10-part series of papers on the species' ecology. For information on the genetics of northern wild rice, see ref. 16. Surveys of some of the other literature may be found in refs. 3 and 17. For a practical summary of wild rice's ecology relevant to this paper, see ref. 2.)

1.3.1 Growth

Z. palustris has a limited range of suitable water depths, between 0.15 and 0.9 m (0.5 and 3 ft).[17] It typically grows in aquatic areas with some sort of flow, such as lakes with an inlet and outlet, tributaries, or small creeks and rivers. There are two critical growth stages: (1) Initial germination (occurring in early to mid-spring), and (2) the floating leaf stage (occurring in early to mid-summer). In order for the seedling to germinate, a minimum 3-to-4-month dormancy period in near-freezing waters is needed. Germination then occurs when waters reach about 4 °C (40 °F).[3] During the floating leaf or emergent phase, *Z. palustris* begins exchanging gases with the atmosphere and develops buoyancy. During this stage, the rice beds are extremely susceptible to changes in water level and flow changes, as the rice can drown and also be uprooted by its own buoyancy because of its shallow root base.

A number of things can seriously damage the rice production in a given locale. Variation in water level is a well-known problem. Excess inflow (precipitation or change in the upstream watershed), restricted outflow (by beaver or manmade), storms, carp, other wild life, disease, insects, and competition from native and invasive species can all eliminate a substantial portion of the rice production.

1.3.2 Boom-Bust Cycle

It is commonly stated that northern wild rice exhibits a boom-bust cycle. Walker (ref. 18), the Minnesota Department of Natural Resources (ref. 3), and others—such as John Pastor and Tali Lee in their successful proposal to the National Science Foundation (Division of Environmental Biology Application 0715808)—state that such cycles occur; but none of the sources examined offer supporting citations or substantiating data. One of the goals of this study was to substantiate the existence of the cycle and characterize it.

The only reference the author has been able to find that provides data demonstrating such a boom-bust cycle is ref. 19. Their figure 1 shows, for the period 1970–1987, a clear boom-bust cycle simultaneously affecting the commercially grown wild rice harvested in both the Provinces of Manitoba and Ontario, while no cyclic behavior is seen in Saskatchewan. The observed cycle is approximately 4–5 years long. It is important to note the data for the figure are production for an entire province. Chapter 3 discusses a province-wide drop in standard deviation of density from 1984 to 1985 for all 20 of the study lakes in Saskatchewan. However, the subsequent 2 years exhibit considerable heterogeneity lake to lake.

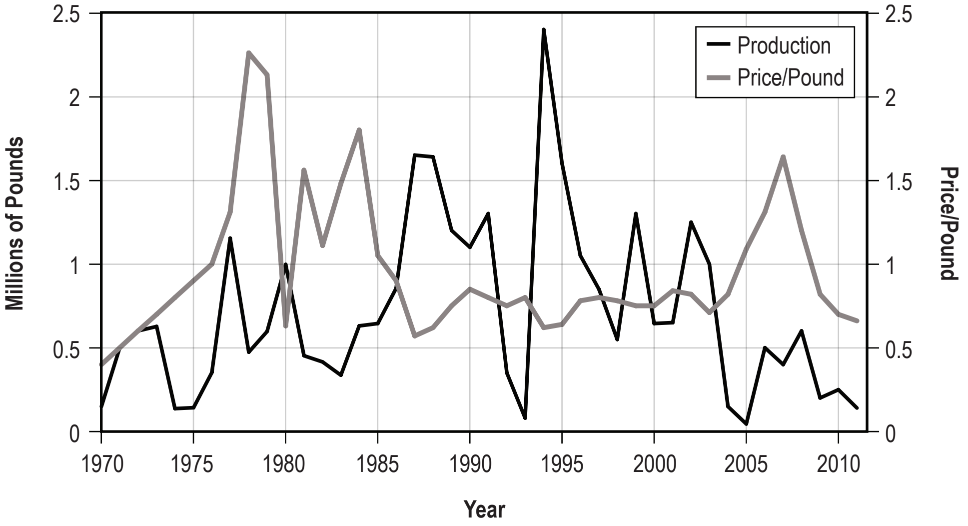

Figure 1. Production of wild rice in Manitoba and price per pound in Canadian dollars.

The Province of Manitoba has subsequently published additional statistics on wild rice production and price for the period 1970–2011.[20] These data show that the apparent cyclic nature shown by reference 19 was probably not caused by a boom-bust cycle, as shown in figure 1. The general lack of correlation between price/pound and production indicates variations in production are caused by factor(s) other than the value of the harvest.

With specific attributions, A.E. Jenks reported that multiple individuals, Ojibwe and European Americans, had observed a boom-bust cycle in the wild rice.[21] However, it is also clear, from excerpts from reference 21 (pp. 1095 and 1099) that while a 3-to-4-year boom-bust cycle existed in some areas, in others it did not:

> In some sections of the country the rice crop failed partly or wholly at frequent intervals. Information from such sources as Chief Pokagon and government farmers at Indian reservations shows that it so fails once in three or four years. Again, at Grass Lake, Lake County, Illinois, where there are 1,000 acres of wild rice, it has not been known to fail in the last sixty years.
>
> In some sections of the country the rice crop fails partially or wholly as often as once in three or four years, while in other sections it has not been known to fail for long periods of time.

Figures 1 and 2 of reference 22 do not strongly support a conclusion that a clear boom-bust cycle exists, especially not with a 3-to-4-year or 4-to-5-year cycle period. Significant annual variation (<≈40%) in northwestern Wisconsin is evident, but it does not have the amplitude of the cycles shown in reference 19, nor does the variation carry over into north-central Wisconsin waters.

2. PARAMETERS OF THIS STUDY

2.1 Data Sources

Data for the studies reported herein are from several sources. The data pertaining to the rice was obtained from the GLIFWC with the assistance of their employee, Peter David. (For information on how the data provided by the GLIFWC are obtained, see ref. 22.) The remote sensing related data (air temperature and precipitation) are from the North American Land Data Assimilation System (NLDAS).[23] Shape files defining the lakes and drainages of interest were obtained from reference 24.

2.2 Spatial Relationships

The study area was limited to a portion of the US termed the 'Wisconsin Ceded Territories' (fig. 2). The Ceded Territories are lands granted from the Chippewa to the US government in a series of treaties signed from 1836 to1854.[25] While most of this land was granted to the federal government, the signatory tribes retained their hunting and gathering rights within these territories. This included the right to harvest the maanomin, a right retained today.

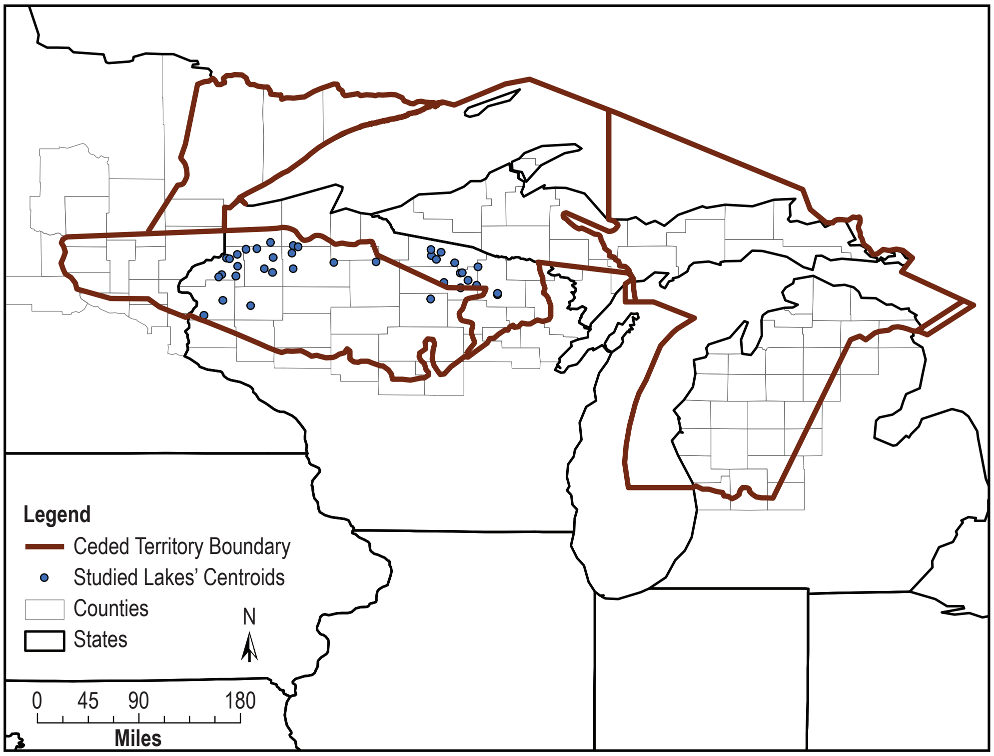

Figure 2. Location of water bodies included in this study and Ceded Territories boundary from reference 26.

For this study, data from 40 northern Wisconsin rice-bearing lakes and riverine systems within the Ceded Territories were used (see figure 2 and table 1). The total east-west distance for the 40 water bodies is approximately 280 km (175 mi). For each of the 40 water bodies, a point location was obtained. Values for each water body were spatially attributed to this point. According to P. David, the 40 water bodies consist of 10 small lakes (<100 acres), 10 medium lakes (100–300 acres), 10 large lakes (>300 acres), and 10 riverine or flowage systems (personal communication, March 27, 2017).

The environmental data shown in figure 2 were obtained as orthogonally gridded cells, which sample a continuous surface. The gridding is 1/8° of the Earth's surface. Cell spacing in the study area is ≈10 km on both axes. For some analyses, the gridded data were resampled to the 12 counties in the study area. This was done by averaging all grid cells whose centroid fell within the county.

Researchers recognized, prior to the work, that analyzing values reported on a per-water body basis against values reported on a county basis would inherently introduce a noise into the analyses. Furthermore, the introduced noise would have extremely complex spatial properties. However, the researchers felt that the magnitude of the added noise was not likely to cause a serious degradation of the analytical results, as the gridded surface had relatively low amplitude features at the scale of the counties.

Table 1 is a list of water bodies included in the study. The maximum acreage for each water body is the largest acreage of wild rice recorded for the period 1985–2013. The maximum rice acreage for some water bodies is larger than the indicated size of the water body because of differences in how the water body size is computed in the different databases used to assemble the table. The Dam column indicates whether or not the water body is a dammed drainage. A 1 ft dam is a dam that is ≈1 ft high. An en-dash (–) indicates the area or status is unknown.

Table 1. Water bodies in study.

County	Name	Max. Rice Acreage	Area (Acres)	Latitude	Longitude	Dam
Barron	Sweeny Pond*	40	26	45.392	–91.949	NF
Bayfield	Totogatic Lake	440	538	46.168	–91.403	No
Burnett	Bashaw Lake	55	170	45.774	–92.141	No
Burnett	Briggs Lake	46	54	46.003	–92.263	No
Burnett	Gaslyn Lake	60	161	45.9	–92.117	No
Burnett	Long Lake	140	329	45.766	–92.361	No
Burnett	Mud Lake (2)	23	26	45.997	–92.221	No
Burnett	Upper Clam Lake*	220	1,338	45.793	–92.325	Yes
Burnett	Webb Creek*	20	10	46.054	–92.121	Yes
Douglas	Mulligan Lake	55	74	46.208	–91.694	No
Forest	Atkins Lake	140	150	45.655	–89.046	No
Forest	Indian/Riley Lake	20	220	45.537	–88.779	No
Forest	Pat Shay Lake	100	117	45.891	–89.033	No
Forest	Rat River*	48	–	45.53	–88.651	No
Forest	Wabikon Lake	90	513	45.551	–88.779	No
Lincoln	Alice Lake	168	1,438	45.483	–89.638	Yes
Oneida	Fish Lake*	80	71	45.624	–89.256	No
Oneida	Little Rice Lake (1)	30	26	45.812	–89.258	No
Oneida	Rice Lake (3)	118	122	45.818	–89.231	1 ft
Oneida	Spur Lake	110	113	45.72	–89.157	No
Oneida	Wisconsin River*	180	1,372	45.694	–89.467	Yes
Polk	Rice Bed Creek*	40	–	45.47	–92.265	No
Polk	Rice Lake (1)	90	90	45.272	–92.551	No
Polk	White Ash Lakes	35	147	45.448	–92.311	No
Price	Blockhouse Lake	50	241	45.958	–90.338	No
Sawyer	Billy Boy Flow*	45	71	45.87	–91.403	Yes
Sawyer	Blaisdell Lake	110	341	45.948	–90.882	No
Sawyer	Pacwawong Lake	135	148	46.15	–91.341	No
Sawyer	Phipps Flowage*	65	134	46.069	–91.422	No
Vilas	Allequash Lake	245	406	46.037	–89.629	No
Vilas	Little Rice Lake	54	50	46.114	–89.635	No
Vilas	Manitowish River*	32	–	46.108	–89.841	No
Vilas	Partridge Lake	35	235	46.08	–89.506	No
Vilas	Rice Lake (4)	50	79	45.944	–89.331	No
Vilas	West Plum Lake	50	69	45.987	–89.565	No
Washburn	Dilly Lake	35	71	45.867	–91.774	No
Washburn	Potato Lake	24	224	45.82	–91.672	No
Washburn	Rice Lake (2)	80	92	46.122	–91.871	NF
Washburn	Spring Lake (1)	43	31	46.12	–92.009	No
Washburn	Tranus Lake	110	166	46.014	–91.665	No

2.3 Rice Measurements

Two measurements and a derived value pertaining to wild rice were used in this study. The two measurements were rice acreage and rice density. The derived value was rice index. Rice acreage is the acreage of rice on each water body. Rice density is the quantity of wild rice in a single acre on a scale from 0 (none present) to 5 (most abundant). P. David, who helped set up the survey, stated the scale was intended to be approximately linear (personal communication, March 27, 2017). A ‘5’ was designed to represent 80–100 (or more) stalks per square meter, and a ‘1’ was designated to represent 0–20 stalks per square meter. Densities designated as 2, 3, or 4 are at 20 stalks-per-meter intervals. Rice index is the product of acreage multiplied by density. Therefore, rice index is an estimate of rice plant abundance in a single body of water. It is important to emphasize that rice density, acreage, and index are not equivalent to production, harvest, or yield.

Data for the three measurements are obtained annually by visual estimation via ground and aerial surveys. GLIFWC has done the work for a number of years and form the longest consistent record of northern wild rice known to the authors. The two rice measurements are available for each of the 40 water bodies for each of the years 1985–2012, save for a few missing water body–year combinations. No information is available that numerically characterizes either the accuracy or precision of the measurements. As suggested by P. David (personal communication, March 27, 2017), analyses should be sensitive to these two points.

It is important to note that rice density is not a continuous measurement; in other words, a value of 2.5 is not possible. The values are binned intervals. In this respect, density is an interval scale.[27] Because of the binning, it is conceptually possible that a water body that has a density of 3 in 2 years, if more precision were available, might be 2.5 in year 1 and 3.49 in year 2. This also means that small numeric differences in computed values, such as average change in density, probably have little physical significance.

Finally, binning inherently introduces a noise compared to a continuous variable. This can be easily recognized if one considers the Fourier transform of a binned function versus that of a continuous function. The significance of this added noise depends on the details of the numerical operations and the magnitude of other signals in the data.

2.4 Temporal Variables

In addition to year, for some analyses, date ranges within a year were defined for three growing stages of wild rice. Germination was defined as 4/25–5/10. Floating leaf stage was defined as 6/10–6/25. The total growing season was defined to be 1/1–7/31. January 1 was used to capture snow as part of the precipitation data and for convenience, as NLDAS data are separated by year. No attempt was made to adjust the date ranges to compensate for either annual variations or geographic variation across the study area.

2.5 Environmental Variables

The NLDAS data were used as the source for air temperature and precipitation because the variables are presented in a uniform manner. The values are already surfaced, the algorithms used to create the data have been validated, and the data are freely, readily and publically accessible.

Daily temperature and precipitation from the NLDAS climatological forcing data were obtained for an area encompassing the 12 counties containing the 40 lakes of interest. Daily temperature was obtained by averaging the 24 hourly values in NLDAS. Precipitation was the daily total for the cell. As previously stated, county values were obtained by averaging all grid cell centroids that fell within the county.

2.5.1 Dammed Versus Undammed

Water level and changes in water level are known to be very important in the biology of *Z. palustris*.[3] There are a number of ways the water level in the lakes supporting wild rice can change. Significant precipitation in the watershed or a beaver dam, especially on a lake's outlet are both possibilities. Control of water levels by manmade dams or control structures is another possibility. The GLIFWC provided lake damming data as GIS files for this study. Each water body was categorized as either dammed or undammed.

2.6 Discussion of Variables

Although only a fraction of the known parameters are considered here, the total number of variables in this study is still substantial. The temporal variables are year and several biologically relevant subsets. Spatial variables include water body size, geographic location, and various aggregation schemes, such as all water bodies in a county or subdividing water bodies based on north versus south or east versus west axes. Environmental variables include precipitation and temperature with the limits of the selected temporal range. Whether a water body is subject to water level/flow control is also a variable. Finally, there are the acreage and density of the rice. Thus, at the finest granularity, a datum has the following four dimensions: (1) time, (2) location, (3) environment, and (4) rice. Given the constraints of time and other resources, an exhaustive investigation of all the variable space was not practical. What was done should be considered only a survey of the variable space.

There are also an indeterminate number of uncontrolled, unmeasured, and often unidentified, variables that affect the data. For example, there are multiple differences between each water body's upstream drainage, such as the geology and agricultural usage. The species and number of fish can strongly affect the rice.[28] Plant disease and insect infestation are active in the environment. Storms can destroy a water body's rice crop. All of these, and more, add to the variation in rice acreage and density between water bodies and for the same water body between years.

3. ANALYSES

3.1 Variation in Water Body Size

A major factor in the analysis of the data is the wide range in water body size. For example, the maximum rice acreage of Totogatic Lake is 22× that of Webb Creek (see table 1). This disparity will significantly affect any analysis where water body size is a factor. Therefore, in several of the analyses reported here, water body size has been normalized by one of two methods. One method uses the maximum reported rice acreage for the water body. The other method uses the average rice acreage for the water body. The former, which is the default logic in this report, has the advantage that all normalized values are between 0 and 1. Its disadvantage is that the annual values inherently tend to be in a limited portion of the available dynamic range. The latter method, using the average for normalization, has the advantage that the dynamic range is numerically wider, but the dynamic range varies between water bodies. The median rice acreage cannot be used for normalization, as some water bodies have 0 acreage for more than half of the years.

3.2 Annual Variation of Rice Acreage and Density Among Water Bodies

The range of normalized acreage for most years is 0–1, meaning that in any given year, at least one of the water bodies is at its maximum reported rice acreage, and at least one water body had no rice acreage. Only 9 years have a maximum value below 1, and all 9 of those years have maximum values ≥0.83. Two years have a minimum greater than 0.

Standardized deviation of the normalized rice acreage was obtained, see figure 3. The limited range of standard deviation from year to year strongly demonstrates that the sampled 40 water bodies have similar variation between water bodies within a year. It is noteworthy that the standard deviation has not changed noticeably while the normalized average acreage has dropped by at least half.

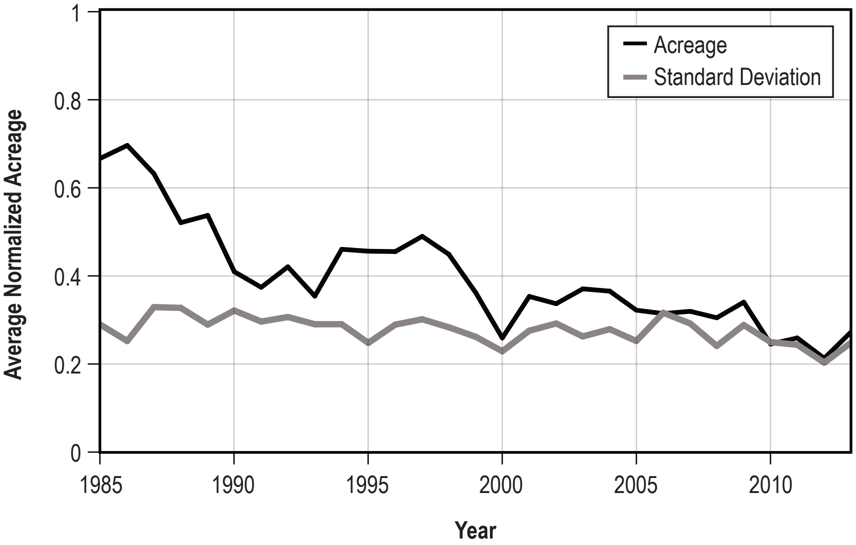

Figure 3. Average over all water bodies of annual normalized rice acreage and standard deviation.

The range of density is similar in behavior to the range of acreage, uniformly 0–5 in almost all years. The standard deviation of density (fig. 4), is also similar in nature to the standard deviation of acreage–fairly consistent irrespective of a long-term drop in average density, which is shown in figure 5. The variation of rice acreage and rice density between water bodies in a single year is very large. This is a major signal in the dataset.

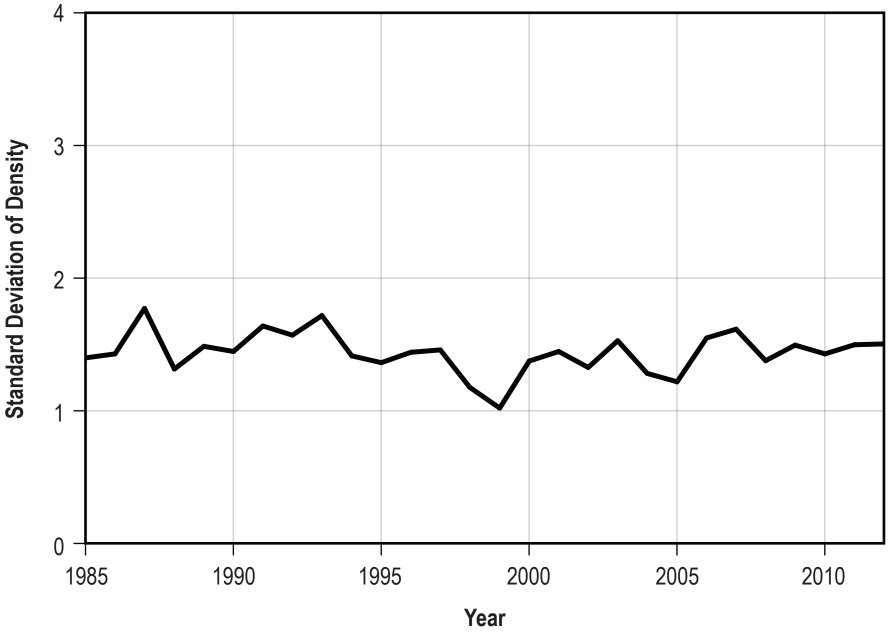

Figure 4. Standard deviation of rice density for all water bodies within a year.

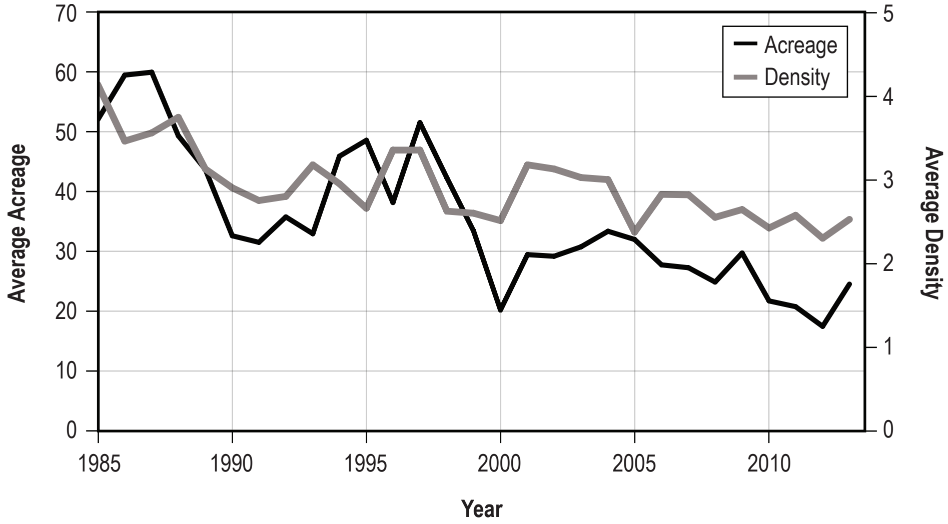

Figure 5. Average rice acreage and density of the water bodies.

3.3. Interannual Variation of Rice Acreage and Density Within Water Bodies

The interannual variation in rice acreage (fig. 6) is computed by the following algorithm:

(1) The water body's average rice acreage over the time period 1985–2012 is computed.

(2) For each water body, the annual acreage is divided by the water body's average rice acreage. This removes the effect of large versus small water bodies.

(3) The difference between the normalized acreages for sequential years is then computed.

(4) For each water body, the average of all the annual differences is then obtained.

There is large interannual variation in the rice acreage for the water bodies. This may be the most striking pattern in the data. Eighty-five percent of the water bodies in the study have an average interannual variation between 30% and 70%. In other words, it is common for rice acreage to change by 50% year to year. Sweeny Pond typically varies more year to year than the average of its rice acreage. The annual acreage of Totogatic Lake (marked 'Largest' in fig. 7) varies year to year by 89%.

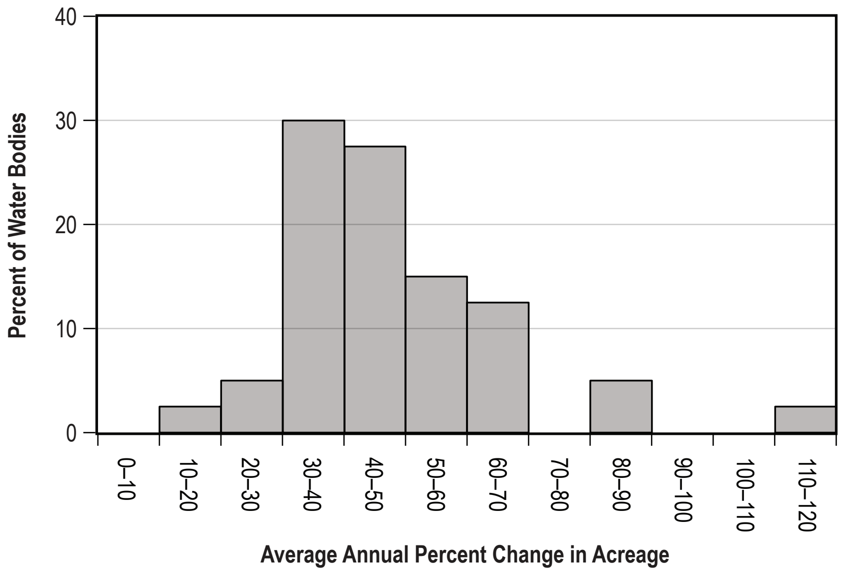

Figure 6. Frequency of the average variation in rice acreage for a water body.

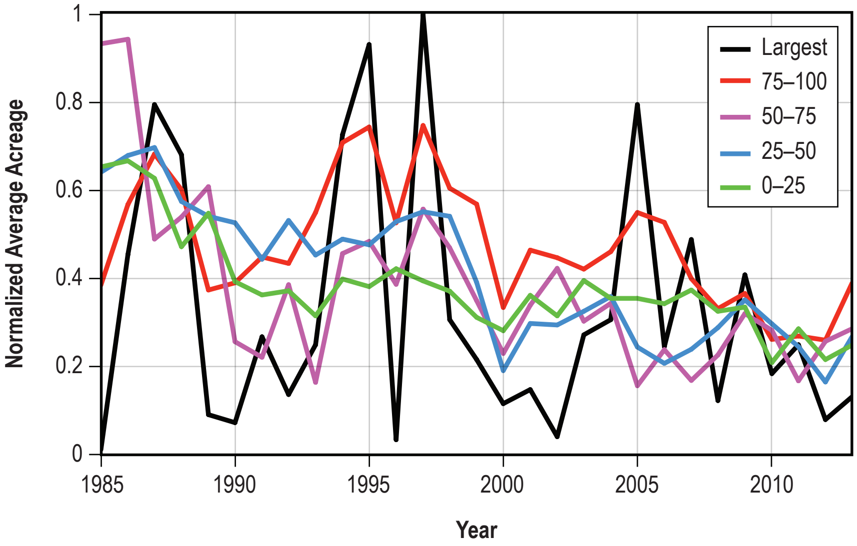

Figure 7. Average normalized rice acreage for water body quartiles, which are defined based on maximum rice acreage for each water body.

There is no obvious pattern to the interannual variation of acreage based on lake versus flowage or the size of the water body. This intense interannual variation obscures most other variations, and it is not explained by the variables examined in this study.

The existence of a boom-bust cycle can be readily checked using the interannual variation data and the following logic: Compare the acreage in a water body in year 1 to the acreage for the same water body in year 2. If the acreage increases in the second year compared to the first year, a flag value of 1 is recorded. If instead the acreage decreases, a flag value of –1 is recorded. If no change between the years is observed, a flag of 0 is reported. When this operation is done for the 40 water bodies for all the years, the sum of the flag values is 1,094 (12 year-water body data points are missing), is +20.

Compare this to what would be expected if a 4-year boom-bust cycle existed. For a single water body, for each cycle, three 1s would be recorded and one –1, with a sum for the cycle of +2. A 3-year cycle would have a sum of +1. Using a 4-year cycle, if it existed consistently, over all the water bodies for all the years, the global sum would be 7 (number of possible 4 year cycles) × 40 (number of water bodies) × 2 (value of a cycle) = 560. If interannual variation in acreage was random, the value would tend to 0. These data strongly support a hypothesis that interannual variation is effectively random, rather than a hypothesis that a multiyear boom-bust cycle exists.

There is also interannual variation in rice density. A check for a possible boom-bust cycle in density can be done in exactly the same way as for acreage. When this is done, the sum is +31, which is essentially what would be expected from random interannual variation. The magnitude of the average interannual density variation is small. Thirty-eight of the water bodies have an average variation less than 0.18 units. The other two water bodies have average variations of 0.35 and 0.25 units.

A check was made to see if acreage and density vary in a correlated manner. This was done by comparing the corresponding flag values for each water body for each year. If both flags were +1 or both were –1, a second flag of +1 was recorded. If the acreage and density flags had different signs, a second flag value of –1 was recorded. If the flag for either density or acreage was 0, a second flag of 0 was recorded. With this logic, the second flags were then summed. It was found that out of 1,093 water body–years, rice density and rice acreage both increased, or both decreased 486 times. Either density or acreage stayed the same 377 times. The density changed with an opposite sense of the change in acreage only 230 times. This is strong support for the conclusion that density and acreage do co-vary, but the relationship is not extremely strong.

3.4 Multiyear Variation in Rice Acreage and Density Within Water Bodies

In addition to the interannual variation, there are variations in rice acreage and density that occur on longer time spans. Figure 5 shows the average acreage of wild rice in the surveyed water bodies versus year. Nineteen of the years have data for all 40 water bodies. Seven of the years have data for 39 water bodies. The remaining 3 years have 38, 37, and 36 water bodies.

There is no evidence of a boom-bust cycle when the data are examined this way. However, there are several very important observations that can be drawn from the two curves: Over the almost three decades of measurement, the expected acreage has dropped by approximately 50%. Density also clearly shows a long-term decrease, though the magnitude of total decrease in density is not as large as that seen in the acreage data. Another observation is there can be strong (≈50%)

variations in acreage over 4-year periods. Although there are variations in density over time periods shorter than a decade, density clearly does not vary in the same way as acreage or in synchrony with acreage.

Points 1 and 2 together suggest that at least two phenomena can substantially affect acreage. One of the phenomena might or might not also affect density. Whatever the phenomena are, they can operate over hundreds of kilometers.

Approximating the large swings in average acreage over multiple years, e.g. 1987–1990 and 1997–2000, by the summation of a random variable acting on the 40 water bodies is possible; however, this possibility was not quantitatively investigated. Even if this were regarding this data, it certainly would not seem to apply to the rice harvest in Manitoba, which shows even larger, sharper swings (fig. 1).

Domination of the average acreage by a few large water bodies is also conceptually possible. For example, at its maximum coverage, Totogatic Lake in Bayfield County contains 1/8 of the total maximum rice acreage (see table 1). This possibility can be checked by normalizing the annual acreage in each water body by the maximum acreage observed for that water body. This was done, and the average normalized acreage plotted versus year (fig. 3). Similar patterns are present in figure 3 as in figure 5, though they are reduced in amplitude because of the method of normalization (using the maximum rice acreage for each water body, thus values are constrained to the range 0–1). This suggests that a few large water bodies are not driving the observed patterns. As the dynamic range of density is 0–5 in steps of 1, normalization of density was not needed.

The phenomena can possibly acting on the average water body acts differently as a function of water body size. This was checked by grouping the water bodies into quartiles and plotting the average normalized acreage for each quartile (see fig. 7). There are four water bodies in the 75-to-100 rice acreage quartile, five in the 50-to-75 quartile, 10 in the 25-to-50 quartile, and 21 in the 0-to-25 quartile. Also shown is the normalized rice acreage for Totogatic Lake, which has the largest maximum rice acreage of the 40 water bodies. Note the swings in acreage that one water body exhibits. There is no clear difference in normalized average rice acreage that is related to the maximum rice acreage.

3.5 Environmental Variables

For this work, daily average temperature and daily precipitation for each NLDAS grid cell were obtained for the entire year. Annual mean precipitation and annual mean temperature were obtained for each county by averaging all the daily precipitation or temperature values for all grid cells whose centroid fell within the county. This process obtains an approximation of a more rigorous area weighted average while simplifying processing details.

For each year, seasonal mean temperatures for each of the three seasons—germination, floating leaf, and growing—were obtained for each county by averaging all the daily temperature values during the season for all grid cells whose centroid fell within the county.

The three seasonal precipitation values data were handled differently. As for temperature, a daily precipitation value for the county was obtained by averaging all the daily precipitation value for all grid cells whose centroid fell within the county. Then, for each year and each county, the daily precipitation for each of the three seasons were summed over the season's time period. This gave a season total precipitation by county for each year.

In total, there are eight values for each county for each year—annual mean precipitation and temperatures, season mean temperatures for three seasons, and season precipitation summations for three seasons. Values are obtained by the methods explained in sections 2.5 and 3.6. To permit plotting on a single axis, the daily average values were multiplied by 271, and the growing season values were multiplied by 0.128.

As stated previously, the variations in rice acreage within a year and between years are both very large. In contrast, variation of precipitation and temperature across the 12 counties in a single year is much smaller than the variation for a single county across the 28 years, 1985–2012 (see table 2). Stated another way, the variation between years for a county is much greater than the variation within a year between counties. Any analysis using values by county would have substantially more noise than an analysis using values by year. Therefore, analyses were done on a yearly basis.

Table 2. Comparison of average standard deviation by county versus by year.

	Germination Season	Floating Leaf Season	Growing Season	Annual
	Standard Deviation in Precipitation			
For 12 counties	23.6	31.1	99.4	0.37
For 28 years	10.1	13.5	37.8	0.15
	Standard Deviation in Temperature			
For 12 counties	4.4	3.6	2.7	2.06
For 28 years	1.3	1.5	0.8	0.65

Figures 8 and 9 show the four precipitation and four temperature variables examined in this study versus year. None of the eight plots show clear trends or patterns with time. The fact that there is no spatial component to these plots is emphasized.

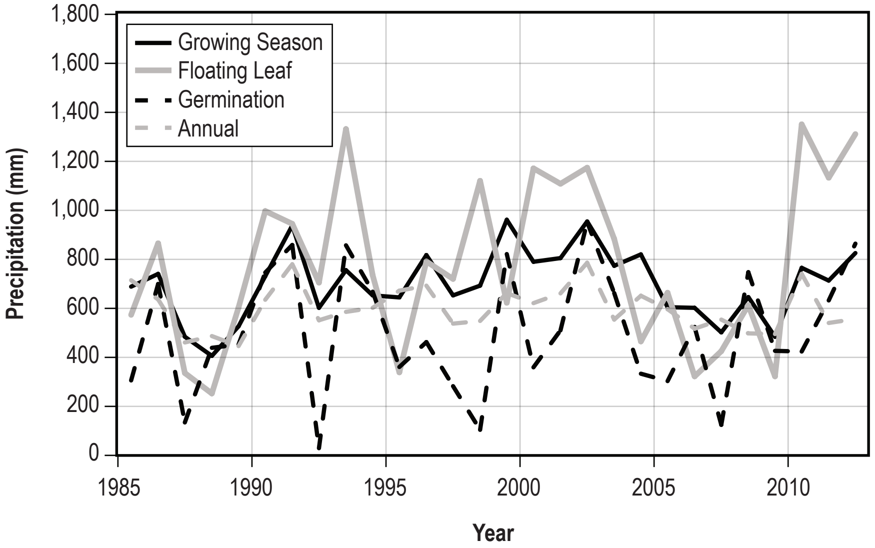

Figure 8. Annual variation and long-term trend in precipitation for the daily average, germination season, floating leaf season, and growing season.

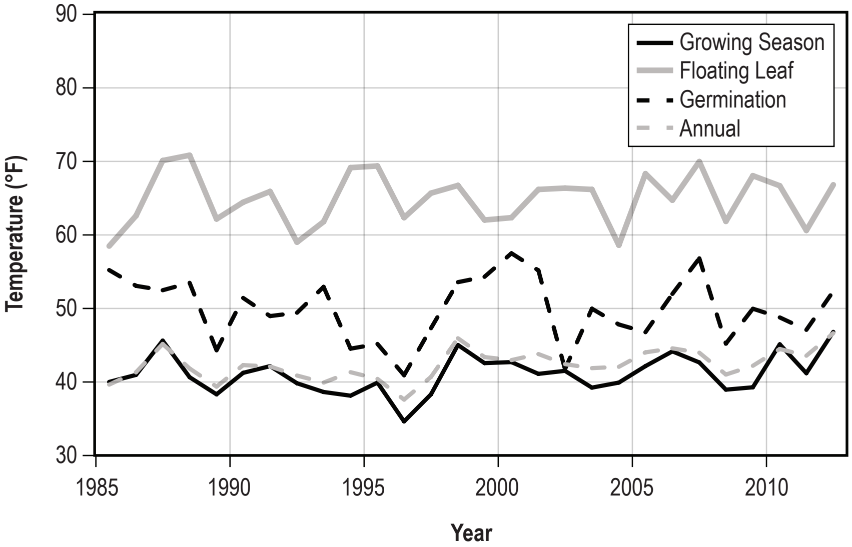

Figure 9. Annual and long-term variation in temperature for the daily average, germination season, floating leaf season, and growing season.

3.6 Environmental Variables Versus Rice Variables

The relationships between temperature or precipitation versus rice acreage, density, or index were investigated by examining the annual average of each of the three rice measures across all water bodies versus the corresponding yearly average or seasonal summation precipitation or the average temperature. This made a total of 24 graphs. Figures 10 and 11 are typical of many of the graphs that do show a relationship. Again, emphasizing these graphs show no spatial relationships; but they show time- environment-rice is important.

Table 3 shows which of the 24 graphs visually exhibit relationships. None of the graphs show notably stronger relationships than those exhibited in figures 10 and 11. When a relationship is seen with rice acreage, acreage is increasing with decreasing precipitation or decreasing temperature. When a relationship is seen with rice density, density is increasing with decreasing temperature.

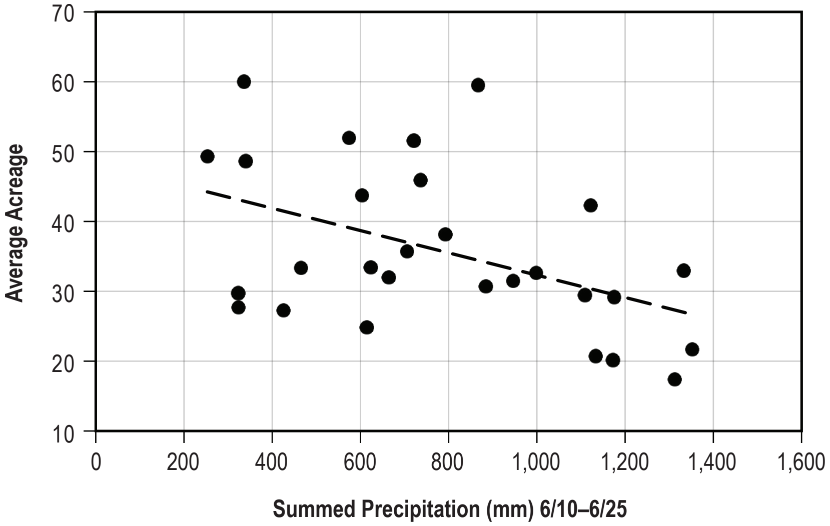

Figure 10. Average rice acreage over all 40 water bodies versus the sum of precipitation during the floating leaf period. The dashed line is the least squares linear fit to the data. R^2 is 0.22 for the line.

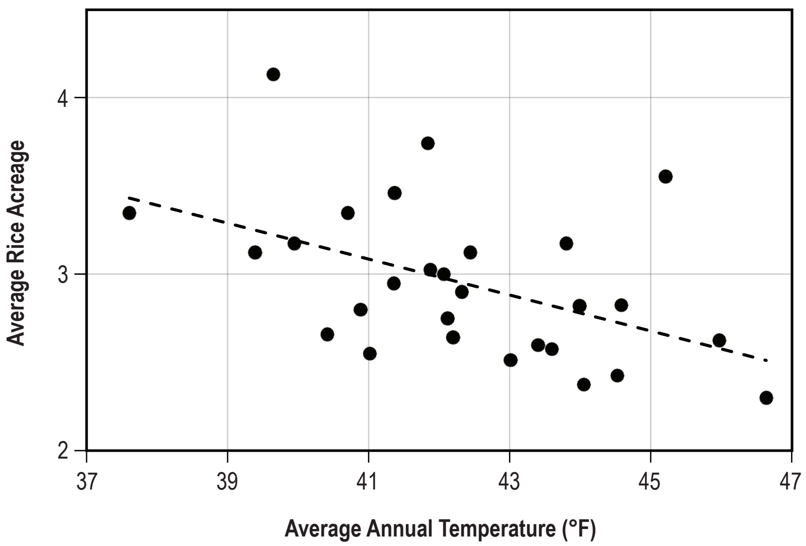

Figure 11. Average annual temperature for all counties versus average rice density for all water bodies. $R^2 = 0.24$.

Table 3. The presence/absence of an apparent relationship between precipitation and temperature for various time periods versus rice acreage, density, and index.

	Time Period	Acreage	Density	Index
Precipitation	Annual	No	No	No
	Growing	Yes	No	Yes
	Germination	No	No	No
	Floating Leaf	Yes	No	Yes
Temperature	Annual	Yes	Yes	Yes
	Growing	No	Yes	Yes
	Germination	No	No	No
	Floating Leaf	No	No	No

Density shows only two occurrences of a possible relationship. It is certain that no strong relationship exists. It may also be true that weaker relationships may be obscured by the binned nature of the variable with its limited dynamic range.

3.7 Effects of Damming

Preliminary analysis appears to show that grouping dammed and undammed water bodies produce no significant difference results. Refinements to the methodology should be considered before completely ruling out manmade water level controls as a factor on these waters.

4. DISCUSSION

4.1 This Study

The choice of variables for this study was largely dictated by data availability and time constraints, not by the biology of *Z. palustris*. For example, biologically, it is highly probable that during germination, it is water temperature—not air temperature—that is relevant; but the latter is available, and the former could only be approximated with modeling that probably has never been done.

The existence of other more meaning variables that have been measured or can be estimated is entirely reasonable. For example, wild rice self-seeds by shattering. The timing and nature of wind could play a significant role in the overall process, and some measurements of wind can be recovered from the meteorological databases. It is also entirely possible that local storms could play a significant role in the variation between water bodies in a single year, and in the interannual variation for a single water body. Storms can damage or destroy the plants during the floating leaf stage. Conceptually, storms later in the growing season could cause lodging, which is a well-known problem with many seed-bearing grasses, such as wheat. In either case, storm damage could greatly reduce the seed supply for the subsequent year. Also, figure 11 and an anecdotal observation from P. David (written communication from April 26, 2017) suggest that colder winter temperatures—which may be obtained from the NLDAS data—could be important, as they might cause better seed germination.

The two biggest signals in the rice data are clearly the variation among water bodies within a year and variation for each water body between years. Metaphorically, these are the elephants in the room. This study has not identified any evidence as to the nature of the processes that are responsible for these variations. Within the limits of this study, it is possible that a single process or a collection of processes causes both. We also emphasize that the strength of the two big signals in the rice data make detection of the weaker signals much more difficult. In fact, it would have been impossible to demonstrate the existence of the weaker signals without the large, long-term dataset.

The lack of a strong relationship between interannual changes in rice acreage and rice density is striking. It means that very large changes in area covered by rice occur without corresponding changes in density. As the coverage of wild rice for a water body generally returns at some subsequent year, it is clear the interannual change is not due to degradation/destruction of the rice bed. This is another major signal in the data without known causative agent(s).

The subtler signals in the data are also unexplained. These include the long-term decrease in acreage and density in the study area and the relationships between some combinations of temporal-precipitation and temporal-temperature versus rice acreage or rice density.

4.2 Other Datasets

For a single water body, the changes in rice acreage year to year raises questions about the spatial patterns of the changes. We point out that knowledge of the changing spatial patterns on an interannual basis could be useful in building or restricting hypotheses about the cause(s) of the interannual variations. Vogt refers to a library of imagery for approximately 80 water bodies in Minnesota covering the time period 2007–2016.[29] P. David has published multiple aerial photographs of rice-bearing waters and has shared some impressive time sequence images with the author (personal communication 4/26/2017). There may be other archives of aerial photographs that would be useful.

Water depth is a major ecological variable for *Z. palustris*. While water depth can be measured multiple ways from a boat, surveying a significant number of water bodies that way becomes a sizeable task. For the type of lake of interest for wild rice, it is very likely this variable can be accurately recovered from multispectral imagery obtained by various satellite-borne instruments. Clear water has moderate transmissivity in bluer wavelengths and decreasing transmissivity into the near-infrared. Analysis of imagery acquired when there is no vegetation on the water body surface can use this change in transmissivity to estimate depth of the water.[30]

There are a number of meteorological variables that can be obtained in surfaced form or can be readily surfaced. Lightning is an excellent proxy for thunderstorm activity. Lightning is measured from space by such instruments as the Lightning Imaging Sensor on the International Space Station, and the Geostationary Lightning Mapper on GOES-16. The National Oceanographic and Atmospheric Administration archives all of the ground-based meteorological data for first-order and co-op stations. Measurements include temperature, humidity, winds, precipitation, cloud cover, and visibility. All of these are hourly data. In addition to temperature and precipitation, as used here, NLDAS also has wind speed, wind direction, and specific humidity (from which relative humidity can be computed). NLDAS land surface model outputs could also be helpful; these include surface runoff, total evapotranspiration, soil moisture at four vertical depths, soil temperature at four vertical depths, vegetation fraction, and snow cover fraction.

4.3 Other Rice Data for Future Work

For future work, study of other wild rice datasets could be valuable inclusions. One such dataset is in reference 29. Data and analyses for 10 lakes measured over the time period 1998–2016 is presented. The publication includes information on multiple variables not readily available or nonexistent for the GLIFWC data used here. The variables include water depth, water temperature, and water quality. The rice parameters measured are density, average stalks per square meter, and biomass, in grams per square meter. One interesting observation in this work shows a decrease in rice biomass over the survey period but not a decrease in acreage.

A second source of data is rice production in Manitoba. The production data (fig. 1) for Manitoba do not show a long-term decline. It could be there is no long-term decline in Manitoba; equally, some change—such as increasing harvesting activity—is masking a decline. The information included here does not illuminate the situation. The Manitoba data does show wild annual swings in production. This is Province-wide data, which suggests that whatever is causing such intense changes in production operates on scales of many hundreds of kilometers. There are various management differences between the Manitoba rice waters and Wisconsin waters, of which any joint analysis would need to be aware.

Genetically, the paddy wild rice is essentially identical to the wild wild rice, though it has a slightly smaller range of characteristics due to selection for characteristics such as resistance to shattering. It would be prudent to investigate the observations and production records of commercial wild rice producers in the region. By creating fields, which are inherently consistent relative to the open, natural system studied here, the farmers may eliminate or control variables which cannot be isolated in a study such as this. It is possible both growers and researchers and the Ojibwe who depend on the wild rice harvest could all benefit from such a collaboration.

4.4 Statistical Significance

Note that this report has purposely avoided the use of parametric statistical analysis to make assertions about significance. This is for several reasons. First, the nature of the underlying distributions is unknown. Secondly, application of the central limit theorem in this case is at best problematic, as it applies to independent, random variables. It seems highly likely that there are multiple dependent, nonrandom variables involved in this system. Whether any or all of the system can be approximated by random variables has not been established. Thirdly, one of the major parameters, rice density, is a binned, low-resolution measure. While the numerical operations required to compute statistical significance can be performed on such data, the meaningfulness of the result may not be as great as expected. Finally, we repeat the axiom ‘Correlation is not proof of causation.’ This study has identified a large number of relationships. It has not identified any causative or controlling forces. Asserting significance inherently tends to obscures this.

4.5 Summary of Observations

To assist the development of future research hypotheses, the major observations of this study are summarized here. An understanding of the ecology of *Z. palustris* should help explain the following observations:

(1) The annual variation of rice acreage and rice density among water bodies is very large. This is a major signal in the dataset.

(2) The consistency of the annual range of rice acreage and density, as well as the limited range of standard deviation from year to year, strongly demonstrates that the sampled 40 water bodies have similar variation between water bodies within a year.

(3) It is noteworthy that the standard deviations of rice acreage and rice density have not changed noticeably, while the normalized average acreage has dropped by at least half, and the average density has also dropped substantially.

(4) There is large interannual variation in the rice acreage for the water bodies. This may be the most striking pattern in the data.

(5) There is no obvious pattern to the interannual variation of acreage based on lake versus flowage or the size of the water body.

(6) Rice acreage can change radically without comparable changes in rice density.

(7) It is clear these data strongly support a hypothesis that interannual variation is effectively random, rather than a hypothesis that a multiyear boom-bust cycle exists.

(8) The data strongly support the conclusion that density and acreage do co-vary, but the relationship is not extremely strong.

(9) Over the almost three decades of GLIFWC measurements, the expected rice acreage has dropped by approximately 50%. Density also clearly shows a long-term decrease, though the magnitude of total decrease in density is not as large as that seen in the acreage data.

(10) There can be strong (≈50%), noncyclic variations in average acreage over 4-year periods.

(11) Although there are variations in density over time periods shorter than a decade, density clearly does not vary in the same way as acreage or in synchrony with acreage.

(12) Whatever phenomena control the long-term trends in average rice acreage and density operates over hundreds of kilometers and many years.

(13) A few large water bodies are not driving the observed patterns.

(14) The maximum rice acreage of a water body does not appear to have a significant relationship to the water body's normalized average rice acreage over time.

(15) When a relationship is seen between rice acreage and air temperature or precipitation, it is such that acreage increases with decreasing precipitation and decreasing temperature.

APPENDIX A—RICE ACREAGE

Data in tables 4–6 are courtesy of Peter David, Great Lakes Indian Fish and Wildlife Commission. As the data are visually estimated, there is the possibility of human variation in the measurements. Mr. David comments in a written communication to D. Rickman (April 26, 2017) that the data for 1985 and 1986 were obtained by his predecessor and that work may have influenced his own work in the early years. Removal of this data from the analyses would not substantially affect the results of this study.

In 2007 Upper Clam Lake developed a problem with carp, possibly due to a loss of blue gill (Havranik, 2012). Intensive restoration efforts have been undertaken since ≈2011. Mulligan Lake has had a beaver dam for several years, which has destroyed the rice habitat.

Table 4. Rice acreage for each lake for years 1985–1995.

	County	Water Body	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
1	Barron	Sweeny Pond	25	15	–	30	5	4	0	9	0	40	1
2	Bayfield	Totogatic Lake	5	200	350	300	40	32	118	60	110	320	410
3	Burnett	Bashaw Lake	25	15	8	20	55	10	8	7	6	8	12
4	Burnett	Briggs Lake	33	37	40	30	33	46	28	36	28	22	30
5	Burnett	Gaslyn Lake	60	60	30	60	10	28	20	14	20	21	26
6	Burnett	Long Lake	140	140	120	100	65	72	55	55	65	85	85
7	Burnett	Mud Lake (2)	20	17	2	–	23	23	18	22	9	10	12
8	Burnett	Upper Clam Lake	200	200	60	70	120	125	140	110	215	190	200
9	Burnett	Webb Creek	12	20	–	0	0	0	20	15	13	10	12
10	Douglas	Mulligan Lake	22	20	10	55	54	33	30	10	50	41	2
11	Forest	Atkins Lake	130	140	15	30	60	1	1	0	0	0	0
12	Forest	Indian/Riley Lake	20	15	4	1	6	2	2	3	2	2	4
13	Forest	Pat Shay Lake	–	–	1	4	15	3	5	64	100	100	90
14	Forest	Rat River	36	35	20	18	15	18	20	48	12	15	15
15	Forest	Wabikon Lake	62	50	90	10	10	4	30	72	16	30	38
16	Lincoln	Alice Lake	168	165	125	5	120	33	7	39	10	9	50
17	Oneida	Fish Lake	37	60	60	70	70	80	8	38	28	20	20
18	Oneida	Little Rice Lake (1)	23	23	30	20	22	20	0	0	0	0	15
19	Oneida	Rice Lake (3)	118	118	0	118	100	1	0	112	0	100	70
20	Oneida	Spur Lake	110	110	96	100	100	15	0	110	110	80	70
21	Oneida	Wisconsin River	–	120	120	180	100	135	120	150	120	180	150
22	Polk	Rice Bed Creek	40	40	–	3	1	2	2	2	11	5	–
23	Polk	Rice Lake (1)	70	25	75	50	60	48	60	76	55	25	–
24	Polk	White Ash Lakes	30	20	35	2	15	5	12	7	9	8	20
25	Price	Blockhouse Lake	10	20	50	50	25	20	12	22	13	20	25
26	Sawyer	Billy Boy Flow	22	30	30	25	45	20	3	20	–	20	8
27	Sawyer	Blaisdell Lake	19	90	100	100	75	95	105	20	40	100	65
28	Sawyer	Pacwawong Lake	100	100	100	100	80	75	90	48	40	105	125
29	Sawyer	Phipps Flowage	11	20	–	40	35	42	65	43	18	42	40
30	Vilas	Allequash Lake	58	60	245	100	75	42	55	66	75	60	75
31	Vilas	Little Rice Lake	9	20	30	15	20	2	2	0	–	4	8
32	Vilas	Manitowish River	–	30	30	10	15	32	8	0	15	12	10
33	Vilas	Partridge Lake	15	25	35	13	20	8	18	15	30	26	12
34	Vilas	Rice Lake (4)	22	15	30	15	50	22	16	20	16	28	28
35	Vilas	West Plum Lake	40	50	23	50	35	5	30	35	10	18	25
36	Washburn	Dilly Lake	30	30	35	30	10	19	15	19	20	16	16
37	Washburn	Potato Lake	23	20	20	5	10	8	18	8	8	15	10
38	Washburn	Rice Lake (2)	48	40	80	30	40	44	26	10	12	18	15
39	Washburn	Spring Lake (1)	30	25	15	25	25	22	18	5	3	12	25
40	Washburn	Tranus Lake	100	100	45	40	90	110	75	40	30	20	28

Table 5. Rice acreage for each lake for years 1996–2007.

	County	Water Body	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
1	Barron	Sweeny Pond	7	15	8	3	5	3	5	20	1	11	0	1
2	Bayfield	Totogatic Lake	15	440	135	95	51	65	18	120	135	350	108	215
3	Burnett	Bashaw Lake	8	8	2	4	7	7	3	6	2	4	1	0
4	Burnett	Briggs Lake	26	35	25	18	22	41	8	12	19	22	30	33
5	Burnett	Gaslyn Lake	18	20	18	23	18	15	7	12	25	5	1	28
6	Burnett	Long Lake	70	115	65	40	20	20	60	20	40	20	65	65
7	Burnett	Mud Lake (2)	18	18	11	6	6	15	12	14	10	10	13	15
8	Burnett	Upper Clam Lake	180	200	210	180	31	125	190	135	165	120	220	15
9	Burnett	Webb Creek	12	10	12	16	20	20	9	11	12	12	20	15
10	Douglas	Mulligan Lake	42	13	10	16	15	18	10	20	38	42	9	23
11	Forest	Atkins Lake	0	0	0	0	0	0	0	0	0	0	0	0
12	Forest	Indian/Riley Lake	3	2	4	5	7	5	11	14	2	3	3	1
13	Forest	Pat Shay Lake	90	100	100	60	4	8	1	0	1	2	1	2
14	Forest	Rat River	13	24	24	21	16	18	22	24	24	22	22	15
15	Forest	Wabikon Lake	40	50	80	30	24	36	65	65	60	55	70	40
16	Lincoln	Alice Lake	28	45	50	20	24	12	30	15	60	55	6	10
17	Oneida	Fish Lake	50	9	40	58	10	14	5	5	6	4	2	7
18	Oneida	Little Rice Lake (1)	0	0	0	0	0	0	0	0	0	0	0	0
19	Oneida	Rice Lake (3)	80	100	100	100	60	70	60	60	22	16	3	3
20	Oneida	Spur Lake	85	85	95	56	25	45	30	68	65	18	8	3
21	Oneida	Wisconsin River	160	140	150	180	165	180	145	125	120	140	150	140
22	Polk	Rice Bed Creek	8	10	8	6	4	15	8	15	–	10	15	15
23	Polk	Rice Lake (1)	90	80	15	15	–	50	40	–	40	30	4	–
24	Polk	White Ash Lakes	13	16	14	10	8	6	9	6	6	7	7	5
25	Price	Blockhouse Lake	26	28	28	2	4	4	1	5	1	1	1	0
26	Sawyer	Billy Boy Flow	5	2	0	3	5	4	15	7	5	7	7	7
27	Sawyer	Blaisdell Lake	75	110	100	75	30	72	95	95	95	90	65	90
28	Sawyer	Pacwawong Lake	80	115	100	67	48	120	135	105	120	24	90	40
29	Sawyer	Phipps Flowage	32	38	35	24	19	18	25	22	25	15	26	5
30	Vilas	Allequash Lake	90	75	80	60	40	35	20	26	30	20	8	65
31	Vilas	Little Rice Lake	4	8	20	16	4	20	23	36	36	36	23	54
32	Vilas	Manitowish River	12	14	15	16	14	16	13	13	11	12	13	14
33	Vilas	Partridge Lake	20	22	27	17	21	18	9	13	18	16	23	24
34	Vilas	Rice Lake (4)	22	20	25	20	10	28	36	43	43	43	28	40
35	Vilas	West Plum Lake	22	20	14	20	2	6	2	20	7	14	2	6
36	Washburn	Dilly Lake	26	24	24	30	21	18	13	16	16	8	11	11
37	Washburn	Potato Lake	22	13	12	9	12	12	24	16	20	8	1	4
38	Washburn	Rice Lake (2)	6	19	14	10	14	11	4	8	8	8	9	7
39	Washburn	Spring Lake (1)	28	15	14	5	–	5	3	4	8	17	43	32
40	Washburn	Tranus Lake	1	4	8	2	2	5	2	3	5	4	3	14

Table 6. Rice acreage for each lake for years 2008–2013.

	County	Water Body	2008	2009	2010	2011	2012	2013
1	Barron	Sweeny Pond	1	8	3	11	3	0
2	Bayfield	Totogatic Lake	54	180	81	110	35	58
3	Burnett	Bashaw Lake	21	0	1	1	0	1
4	Burnett	Briggs Lake	25	21	8	20	10	17
5	Burnett	Gaslyn Lake	6	16	20	4	8	11
6	Burnett	Long Lake	64	120	40	70	58	90
7	Burnett	Mud Lake (2)	4	9	10	4	3	8
8	Burnett	Upper Clam Lake	10	8	10	15	52	75
9	Burnett	Webb Creek	11	9	2	11	12	6
10	Douglas	Mulligan Lake	4	0	0	0	0	1
11	Forest	Atkins Lake	0	0	0	0	0	0
12	Forest	Indian/Riley Lake	2	4	1	4	1	1
13	Forest	Pat Shay Lake	6	15	25	12	2	0
14	Forest	Rat River	13	18	2	12	10	15
15	Forest	Wabikon Lake	70	74	80	55	40	44
16	Lincoln	Alice Lake	20	26	32	30	34	15
17	Oneida	Fish Lake	5	2	1	1	5	10
18	Oneida	Little Rice Lake (1)	0	0	0	0	0	0
19	Oneida	Rice Lake (3)	35	0	10	5	40	4
20	Oneida	Spur Lake	70	0	1	1	2	1
21	Oneida	Wisconsin River	150	165	140	125	120	175
22	Polk	Rice Bed Creek	19	15	10	19	19	16
23	Polk	Rice Lake (1)	15	50	45	24	0	20
24	Polk	White Ash Lakes	10	12	19	14	9	22
25	Price	Blockhouse Lake	0	0	0	0	1	0
26	Sawyer	Billy Boy Flow	16	15	1	19	12	10
27	Sawyer	Blaisdell Lake	50	80	45	95	3	60
28	Sawyer	Pacwawong Lake	35	80	115	16	45	90
29	Sawyer	Phipps Flowage	23	25	14	26	28	16
30	Vilas	Allequash Lake	80	25	10	16	14	28
31	Vilas	Little Rice Lake	45	48	8	12	16	9
32	Vilas	Manitowish River	14	17	16	14	12	15
33	Vilas	Partridge Lake	22	20	20	22	10	23
34	Vilas	Rice Lake (4)	30	36	36	12	4	10
35	Vilas	West Plum Lake	5	12	14	18	15	21
36	Washburn	Dilly Lake	2	2	5	1	1	4
37	Washburn	Potato Lake	13	20	7	21	20	11
38	Washburn	Rice Lake (2)	9	–	5	5	9	7
39	Washburn	Spring Lake (1)	18	3	1	1	2	3
40	Washburn	Tranus Lake	18	26	32	5	44	85

APPENDIX B—RICE DENSITY

Data in tables 7–9 are courtesy of Peter David, Great Lakes Indian Fish and Wildlife Commission. For comments, see Appendix A.

Table 7. Rice density for each lake for years 1985–1995.

	County	Water Body	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
1	Barron	Sweeny Pond	5	1	–	5	1	1	0	4	0	4	3
2	Bayfield	Totogatic Lake	1	5	4	3	2	2	2	2	3	2	4
3	Burnett	Bashaw Lake	5	2	1	3	3	2	3	3	4	3	1
4	Burnett	Briggs Lake	5	5	5	3	3	4	5	4	4	3	3
5	Burnett	Gaslyn Lake	5	4	5	3	3	4	4	3	5	2	2
6	Burnett	Long Lake	1	2	5	3	1	2	2	3	5	3	3
7	Burnett	Mud Lake (2)	5	4	3	–	1	3	3	4	2	4	5
8	Burnett	Upper Clam Lake	5	4	5	5	5	3	1	3	3	3	4
9	Burnett	Webb Creek	5	5	–	0	0	0	5	5	5	5	5
10	Douglas	Mulligan Lake	1	1	1	3	5	2	2	1	1	1	1
11	Forest	Atkins Lake	5	2	1	3	1	1	1	0	0	0	0
12	Forest	Indian/Riley Lake	3	2	1	5	1	2	4	3	4	4	2
13	Forest	Pat Shay Lake	–	–	1	1	2	1	1	1	3	1	1
14	Forest	Rat River	5	5	5	5	5	5	5	5	5	5	2
15	Forest	Wabikon Lake	3	2	2	1	1	3	4	3	4	3	1
16	Lincoln	Alice Lake	4	5	5	3	3	3	3	1	4	4	2
17	Oneida	Fish Lake	5	3	1	5	4	5	4	5	5	3	2
18	Oneida	Little Rice Lake (1)	5	3	5	5	3	4	0	0	0	0	3
19	Oneida	Rice Lake (3)	1	3	0	5	3	1	0	2	0	1	1
20	Oneida	Spur Lake	5	5	3	5	5	1	0	2	4	5	4
21	Oneida	Wisconsin River	–	5	5	3	5	5	5	4	5	5	5
22	Polk	Rice Bed Creek	5	5	–	5	5	5	3	5	5	5	–
23	Polk	Rice Lake (1)	5	4	5	3	5	3	3	3	5	2	–
24	Polk	White Ash Lakes	3	1	5	3	3	2	3	4	4	2	2
25	Price	Blockhouse Lake	5	4	5	5	3	5	2	3	3	3	2
26	Sawyer	Billy Boy Flow	5	4	5	3	5	2	1	1	0	1	1
27	Sawyer	Blaisdell Lake	3	3	3	5	5	4	2	2	2	3	2
28	Sawyer	Pacwawong Lake	5	4	5	5	5	3	2	1	2	3	4
29	Sawyer	Phipps Flowage	5	5	–	5	3	3	4	5	4	3	3
30	Vilas	Allequash Lake	4	4	5	5	2	4	5	5	5	4	3
31	Vilas	Little Rice Lake	5	3	1	3	3	1	2	0	0	1	1
32	Vilas	Manitowish River	–	5	5	5	5	5	5	0	4	4	4
33	Vilas	Partridge Lake	4	5	5	5	3	3	5	5	5	5	3
34	Vilas	Rice Lake (4)	5	1	2	3	1	5	5	3	4	4	2
35	Vilas	West Plum Lake	4	2	5	3	3	1	5	4	4	4	3
36	Washburn	Dilly Lake	5	5	5	5	5	5	3	4	3	3	5
37	Washburn	Potato Lake	5	2	3	5	3	3	2	3	4	2	3
38	Washburn	Rice Lake (2)	5	4	5	3	3	4	2	2	4	3	3
39	Washburn	Spring Lake (1)	5	5	5	3	3	2	1	3	1	4	5
40	Washburn	Tranus Lake	1	1	1	3	3	2	1	1	2	1	1

Table 8. Rice density for each lake for years 1996–2007.

	County	Water Body	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
1	Barron	Sweeny Pond	5	3	4	3	2	2	3	3	1	2	0	4
2	Bayfield	Totogatic Lake	3	4	3	2	3	3	2	2	2	2	2	1
3	Burnett	Bashaw Lake	3	3	3	2	1	3	3	2	2	2	1	0
4	Burnett	Briggs Lake	4	4	3	2	4	4	4	5	3	3	4	4
5	Burnett	Gaslyn Lake	3	3	3	2	2	3	3	4	4	1	1	4
6	Burnett	Long Lake	2	3	2	2	1	3	2	1	3	2	4	4
7	Burnett	Mud Lake (2)	5	4	3	3	3	3	5	5	4	1	5	3
8	Burnett	Upper Clam Lake	4	3	3	4	2	2	4	3	3	2	4	2
9	Burnett	Webb Creek	5	5	4	3	5	5	4	5	4	3	5	5
10	Douglas	Mulligan Lake	1	2	2	2	4	3	3	4	3	3	2	3
11	Forest	Atkins Lake	0	0	0	0	0	0	0	0	0	0	0	0
12	Forest	Indian/Riley Lake	3	3	3	3	3	5	4	4	3	2	4	1
13	Forest	Pat Shay Lake	2	2	1	2	1	4	3	0	1	1	1	2
14	Forest	Rat River	4	5	4	4	4	5	5	5	5	5	5	5
15	Forest	Wabikon Lake	2	3	3	2	2	5	2	3	4	3	3	4
16	Lincoln	Alice Lake	3	3	1	3	3	4	4	2	3	2	3	1
17	Oneida	Fish Lake	3	4	4	2	2	2	3	2	2	2	2	2
18	Oneida	Little Rice Lake (1)	0	0	0	0	0	0	0	0	0	0	0	0
19	Oneida	Rice Lake (3)	1	1	1	1	1	1	1	1	3	1	1	1
20	Oneida	Spur Lake	5	4	4	3	1	2	2	3	2	2	2	3
21	Oneida	Wisconsin River	5	5	3	3	4	5	5	5	5	5	5	5
22	Polk	Rice Bed Creek	5	5	4	3	4	4	3	4	–	2	4	5
23	Polk	Rice Lake (1)	3	2	1	2	–	3	3	–	4	4	2	–
24	Polk	White Ash Lakes	4	5	3	4	2	4	3	4	4	4	2	3
25	Price	Blockhouse Lake	3	3	2	2	1	1	1	1	1	1	1	0
26	Sawyer	Billy Boy Flow	1	1	0	1	2	2	4	3	2	2	5	2
27	Sawyer	Blaisdell Lake	4	3	4	2	3	3	1	1	2	1	4	1
28	Sawyer	Pacwawong Lake	4	4	4	3	4	3	5	4	5	2	4	3
29	Sawyer	Phipps Flowage	4	5	4	4	4	5	4	3	4	1	5	3
30	Vilas	Allequash Lake	5	5	3	3	3	5	3	4	4	3	2	3
31	Vilas	Little Rice Lake	3	5	3	3	3	4	3	3	4	3	3	5
32	Vilas	Manitowish River	5	5	3	4	5	5	5	5	4	5	5	5
33	Vilas	Partridge Lake	5	5	3	4	4	5	4	4	4	3	3	5
34	Vilas	Rice Lake (4)	4	5	3	4	2	5	4	5	4	3	4	4
35	Vilas	West Plum Lake	5	5	2	2	2	2	3	2	3	3	2	2
36	Washburn	Dilly Lake	4	4	3	4	4	3	4	5	4	4	3	5
37	Washburn	Potato Lake	3	2	3	3	2	2	5	4	4	2	1	3
38	Washburn	Rice Lake (2)	4	3	2	3	4	4	4	3	3	3	3	3
39	Washburn	Spring Lake (1)	4	2	3	3	–	1	2	2	2	2	4	3
40	Washburn	Tranus Lake	1	1	1	2	1	2	2	2	2	3	2	1

Table 9. Rice density for each lake for years 2007–2013.

	County	Water Body	2008	2009	2010	2011	2012	2013
1	Barron	Sweeny Pond	1	3	5	2	1	–
2	Bayfield	Totogatic Lake	1	2	2	3	2	3
3	Burnett	Bashaw Lake	1	0	1	1	0	1
4	Burnett	Briggs Lake	4	4	3	4	5	5
5	Burnett	Gaslyn Lake	2	3	3	2	2	3
6	Burnett	Long Lake	3	4	3	4	2	3
7	Burnett	Mud Lake (2)	4	4	4	5	3	4
8	Burnett	Upper Clam Lake	2	3	2	1	4	4
9	Burnett	Webb Creek	5	4	4	5	5	3
10	Douglas	Mulligan Lake	2	0	0	0	0	1
11	Forest	Atkins Lake	0	0	0	0	0	0
12	Forest	Indian/Riley Lake	1	3	3	2	1	1
13	Forest	Pat Shay Lake	1	2	3	2	1	0
14	Forest	Rat River	3	4	2	3	4	4
15	Forest	Wabikon Lake	4	3	3	3	1	3
16	Lincoln	Alice Lake	3	3	2	3	3	4
17	Oneida	Fish Lake	2	4	1	1	2	1
18	Oneida	Little Rice Lake (1)	0	0	0	0	0	0
19	Oneida	Rice Lake (3)	1	0	2	2	1	1
20	Oneida	Spur Lake	1	0	1	1	1	1
21	Oneida	Wisconsin River	4	4	4	5	5	4
22	Polk	Rice Bed Creek	5	4	3	5	2	4
23	Polk	Rice Lake (1)	3	5	3	2	0	4
24	Polk	White Ash Lakes	3	2	4	3	2	4
25	Price	Blockhouse Lake	0	0	0	0	1	0
26	Sawyer	Billy Boy Flow	3	3	1	2	3	3
27	Sawyer	Blaisdell Lake	3	2	1	2	3	3
28	Sawyer	Pacwawong Lake	2	4	5	2	2	2
29	Sawyer	Phipps Flowage	4	4	3	4	4	4
30	Vilas	Allequash Lake	4	2	3	4	4	4
31	Vilas	Little Rice Lake	3	4	3	4	1	2
32	Vilas	Manitowish River	5	4	5	4	5	4
33	Vilas	Partridge Lake	4	3	3	5	4	2
34	Vilas	Rice Lake (4)	2	4	5	3	3	4
35	Vilas	West Plum Lake	4	3	3	4	3	1
36	Washburn	Dilly Lake	2	2	1	1	1	3
37	Washburn	Potato Lake	3	4	2	3	3	3
38	Washburn	Rice Lake (2)	3	–	1	2	3	4
39	Washburn	Spring Lake (1)	2	1	1	1	3	2
40	Washburn	Tranus Lake	2	2	2	3	2	2

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14. ABSTRACT

The Great Lakes Indian Fish and Wild Life Commission has a 40-year record of wild rice, *Zizania palustris*, in northern Wisconsin. Those data, with precipitation and air temperature from the North American Land Data Assimilation System (NLDAS), were analyzed. Variation among water bodies within a single year and variation of each water body between years are the major signals. A long-term decrease in rice acreage of ≈50% was found, and density has also decreased. Rice acreage and density co-vary to some extent. NLDAS variables change inversely to rice acreage and density. A hypothesis that a boom-bust cycle in northern wild rice exists is strongly contradicted.

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