Makak: Co-designing Environmental Sensors to Protect Manoomin (Wild Rice)

Blaine Rothrock
Northwestern University
Evanston, IL, USA
blaine@northwestern.edu

Eric Greenlee
Georgia Institute of Technology
Atlanta, GA, USA
eric.greenlee@gatech.edu

Yaman Sangar
Georgia Institute of Technology
Atlanta, GA, USA
ysangar3@gatech.edu

Julia McKenna
Northwestern University
Evanston, IL, USA
julia.mckenna@northwestern.edu

William Graveen
Lac du Flambeau Band of Lake Superior Chippewa Indians Natural Resource Department
Lac Du Flambeau, WI, USA
wgraveen@ldftribe.com

Kristen Hanson
Lac du Flambeau Band of Lake Superior Chippewa Indians Natural Resource Department
Lac Du Flambeau, WI, USA
KHanson@ldftribe.com

Melissa Lewis
Lac Courte Oreilles Band of Lake Superior Ojibwe Conservation Department
Hayward, WI, USA
melissa.lewis@lco-nsn.gov

Kathleen Smith
Great Lakes Indian Fish and Wildlife Commission
Odanah, WI, USA
ksmith@glifwc.org

Miles Falck
Great Lakes Indian Fish and Wildlife Commission
Odanah, WI, USA
miles@glifwc.org

Brandon Byrne
Great Lakes Indian Fish and Wildlife Commission
Odanah, WI, USA
bbyrne@glifwc.org

Darren Vogt
1854 Treaty Authority
Duluth, MN, USA
dvogt@1854treatyauthority.org

Kimberly R. Marion Suiseeya
Duke University
Durham, NC, USA
k.suiseeya@duke.edu

Ellen Zegura
Georgia Institute of Technology
Atlanta, GA, USA
ewz@cc.gatech.edu

Josiah Hester
Georgia Institute of Technology
Atlanta, GA, USA
josiah@gatech.edu

Alex Cabral
Georgia Institute of Technology
Atlanta, GA, USA
acabral30@gatech.edu

Abstract

Manoomin, the Ojibwe word for Northern Wild Rice, is a culturally significant food source native to the Western Great Lakes region of North America. For generations, Manoomin stewardship has been central to Ojibwe culture and identity, harvested using traditional methods which respect and enrich its growth. Recent years have shown a decline in Manoomin's natural occurrence due to land-use change and global warming. As part of a broader conservation effort, our team has collaborated with Tribal partners to build *Makak*, a low-cost microclimate sensor that monitors factors affecting wild rice to support Tribal sovereignty. This article details our co-design and pilot deployment in collaboration with four partner organizations. Through this work, we share our experiences, and lessons learned from the co-design process with Tribal partners. With this work, we aim to provide insights to other projects that promote Indigenous-centric participatory, collaborative design methods for conservation and environmental sustainability.

COMPASS '25, Toronto, ON, Canada

ACM ISBN 979-8-4007-1484-9/25/07
https://doi.org/10.1145/3715335.3735460

CCS Concepts

• **Human-centered computing → Empirical studies in HCI**; Ubiquitous and mobile computing design and evaluation methods; • **Applied computing →** *Environmental sciences.*

Keywords

Wireless Sensing, Conservation, Two-Eyed Seeing, Indigenous Knowledge

ACM Reference Format:
Blaine Rothrock, Eric Greenlee, Yaman Sangar, Julia McKenna, William Graveen, Kristen Hanson, Melissa Lewis, Kathleen Smith, Miles Falck, Brandon Byrne, Darren Vogt, Kimberly R. Marion Suiseeya, Ellen Zegura, Josiah Hester, and Alex Cabral. 2025. Makak: Co-designing Environmental Sensors to Protect Manoomin (Wild Rice). In *ACM SIGCAS/SIGCHI Conference on Computing and Sustainable Societies (COMPASS '25), July 22–25, 2025, Toronto, ON, Canada.* ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3715335.3735460

1 Introduction

Wild rice (see Figure 1B) is culturally, dietarily, and ecologically significant for Native peoples in the Great Lakes region of North America. The abundance of Manoomin, the Ojibwe word for wild rice (*Zizania palustris*), has declined nearly a third in the last 100 years [17], with more recent estimations of loss at 6-7% per year [42]. Once occupying most of the eastern half of North America [26] (see Figure 1A), Manoomin is now mostly limited to northern Minnesota, Wisconsin, and Michigan in the United States and some parts of Canada. Conservation and restoration of Manoomin have become critical challenges for Ojibwe people and their allies. Generations of stewardship by Tribal Resource Managers and Knowledge-Holders reveal a host of perturbations that contribute to Manoomin's decline.

Manoomin (see Figure 2) is a hardy annual grass that grows in shallow lakes and tributaries surrounding Lake Superior's coastal wetlands and watershed. Healthy Manoomin growth requires seasonal environmental variations, relying on year-to-year fluctuations in weather to combat invasive plants and promote sediment enrichment. The plant is resilient to weather fluctuations as the seeds can remain dormant in the lakebed or riverbed muck for years. However, recent years have shown a decline in Manoomin due to various disturbances, leading to Manoomin's designation in the Tribal Climate Impact Assessments as amongst the most vulnerable of culturally important species [47, 56]. For example, Manoomin is susceptible to high sulfate levels, prominent in the region due to mining [15], which hinders its growth. Extreme weather conditions such as floods, droughts, wind, and hail can completely wipe out a rice bed in its vulnerable "floating" and "submerged leaf" stages. Further, both invasive [1] and native perennials are outcompeting Manoomin in its remaining habitat. Tribal natural resource departments, state and federal government agencies, and academia have come together to address these challenges. However, the scope of challenges confronting Manoomin is vast and resources are scarce.

The wetlands surrounding the Great Lakes host thousands of shallow lakes and tributaries, making it incredibly difficult to collect representative observations and water samples that could help generate greater insights into the determinants of Manoomin health and abundance. Our team has been working to build a low-cost microclimate sensor that monitors environmental factors that affect Manoomin growth to help ease this monitoring burden and spread a wider net to help US-based Ojibwe Nations and their partners collect data on Manoomin waters. This sensor, *Makak* (see Figure 1C), is co-designed with Tribal partners (many of whom are authors of this article) through an approach that integrates Indigenous knowledge and Western science and respects Tribal sovereignty.

In our engagements with Tribal partners, we often encounter the phrase to do things "in a good way". This phrase comes from the Teachings of the Seven Grandfathers, a set of seven Ojibwe principles that outline the moral foundations for living *a good life* (Ojibwe: mino-bimaadiziwin) and respecting others and all of nature [3]. With these principles as our guide, this article reflects our experiences and attempts to do this work "in a good way", and shares the technical descriptions of our co-designed sensing system and qualitative analysis of our pilot deployment.

In this article, we investigate the potential of using waterborne sensor-based technologies to support Manoomin conservation and monitoring practices with Tribes around the Western Great Lakes. Building on a long history of collaboration, the sensor technologies described here reflect a nearly year-long co-design, deployment, and reflection process with Tribal and Tribal-affiliated scientists. Specifically, our contributions are:

1. We describe the hardware, software, dashboard, technical challenges faced, and co-design methodology of Makak, a battery-powered buoy microclimate sensor system designed to support the governance, management, and protection of Manoomin "in a good way" (Section 4).
2. We detail our pilot Makak deployment with four Tribal partners: the Great Lakes Indian Fish and Wildlife Committee (GLIFWC), 1854 Treaty Authority (1854TA), and the natural resource departments of the Lac du Flambeau (LDF; *Ojibwe: Waaswaaganing-ishkonigan*) and Lac Courte Oreilles (LCO; *Ojibwe: Odaawaa-zaaga'iganiing*) Tribal Nations. To our knowledge, this is the first effort to scale a microclimate sensor that is situated within rice beds and designed specifically for Manoomin protection (Section 5).
3. We share our findings from post-deployment data analysis and semi-structured interviews with Tribal partners and synthesize these findings into lessons for the larger academic community to inspire similar collaborative and respectful conservation efforts (Sections 5 and 6).
4. We present insights for researchers working with Indigenous partners and on Indigenous lands, reflecting on the importance of building relationships, including Indigenous knowledge, and being open to new design directions and suggestions (Section 6).

This work contributes to the growing human-computer interaction (HCI) literature on ecological-focused technologies[30, 31], their integration and co-design with Indigenous peoples [4, 39], and respect for Indigenous data sovereignty [38, 40]. Additionally, this work provides practical guidelines for putting post-growth HCI [54] into practice[2].

2 Background, History of Engagement, and Positionality

The Ojibwe (also known as Anishinaabeg, Ojibway, Ojibwa, and Chippewa) are one of the largest cultural groups in North America (330,000 members). In the mid-19th century, eleven Ojibwe Tribes signed three treaties, ceding 7 million acres to the United States of America in exchange for money, goods, and the right to hunt, fish, and gather in the ceded lands. Among the most important of the treaty-protected practices is harvesting Manoomin, which is used medicinally, for ceremonial practices, and as a fundamental food source.

[1] We utilize this term as it is present in Western scientific texts, but note that many of our Indigenous partners prefer to use the term "visiting relatives"

[2] The qualitative data collected through interviews has been reviewed and deemed exempt by our Institutional Review Board.

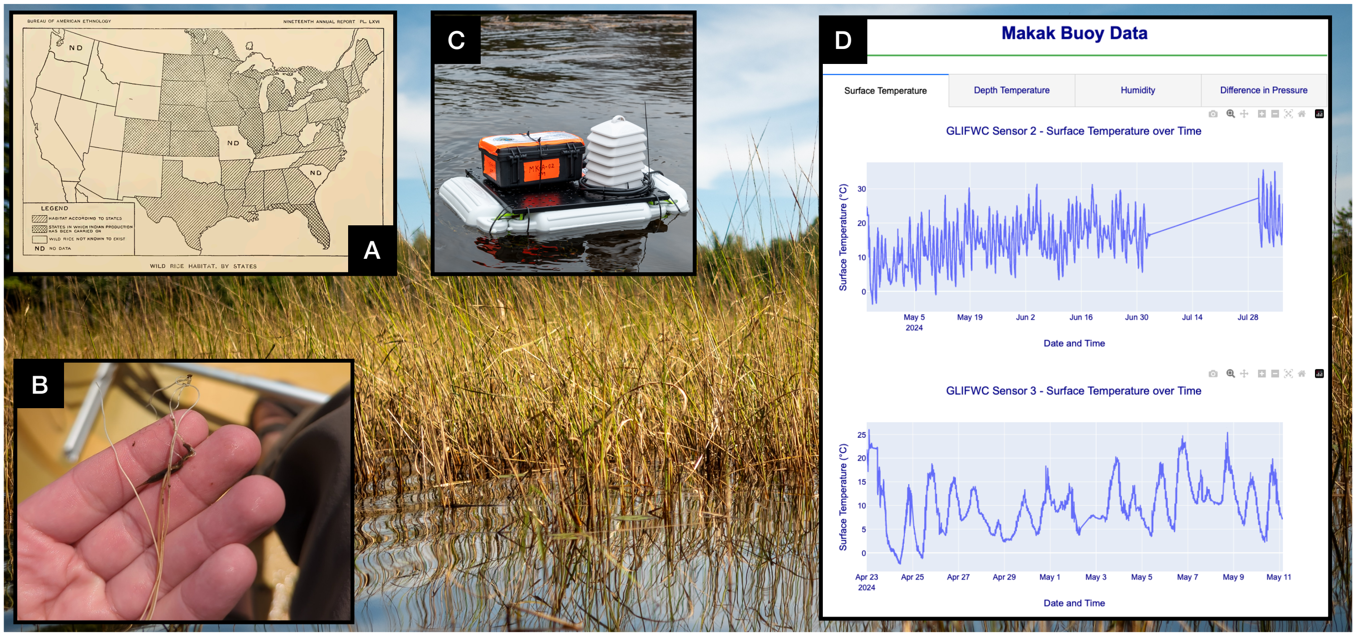


Figure 1: We co-designed and deployed Manoomin (Wild Rice) micro-climate monitoring sensors to assist in conservation efforts with Ojibwe Tribes. (A) The historical distribution of Manoomin across the United States [26], (B) A stand of Manoomin in early-growth in Northern Wisconsin, (C) Our custom-designed Makak buoy sensor system being deployed, (D) a pilot dashboard for partners and Tribal members to view the data from the sensors. The large background image shows a late-season Manoomin bed in Northern Wisconsin.

Manoomin, meaning 'good berry' in Ojibwe (i.e. Ojibwemowin, Anishinaabemowin)[3], is the center of Ojibwe culture and identity [15]. According to traditional knowledge, Ojibwe ancestors migrated to the Great Lakes region following the prophets of the Seven Fires to find a gift, Manoomin, "the food that grows on the water" [3]. In Ojibwe creation stories, Manoomin was created in the second order, after rock, water, fire, and wind (first) and before the animals (third) and humans (fourth) [15]. Manoomin is considered a being and relative, possessing *natural rights*, with the understanding that "wild rice will always be generous to those who gather and use her in a respectful way" [3]. Manoomin conservation is inextricably linked to the survival of the Ojibwe culture, as shown in Figure 2.

Ojibwe Nations use legal tools, environmental data, storytelling, and education to ensure the survival and strengthen the well-being of Manoomin. For example, White Earth Band (Ojibwe: Gaa-waabaabiganikaag) in Minnesota established a Rights of Nature legal case, The Rights of Manoomin, with oil companies laying pipelines [2, 55]. Tribal Nations, environmental conservation groups, state and federal government agencies (i.e., Department of Natural Resources, Environmental Protection Agency), and academic institutions have conducted data collection and restorative work on Manoomin for decades.

[3]We use the term "Manoomin" to refer to the natural growth of Northern Wild Rice, and capitalize the name to respect the rights of nature. However, we recognize its importance to other Indigenous groups, including Dakota who call it 'Psíŋ', Menominee, Ottawa, and others who participate in respectful harvesting.

2.1 History of Engagement and Commitment to Tribal Sovereignty

Our larger consortium began engaging Ojibwe Tribes and GLIFWC in early 2019, initiating conversations around resilience to climate change, sovereignty, data needs, and environmental processes. Since then, we have built relationships and established partnerships among multiple universities, Tribal Nations, and intertribal scientific agencies to co-develop and deploy cyber-infrastructure to support Ojibwe Nations' environmental governance and policy-making, primarily focusing on Manoomin. We have also listened and shared with partners through policy venues such as the Voigt Inter-Tribal Task Force (VTF) [43], an intertribal committee that governs the assertion of treaty rights in ceded territories under the treaties of 1837 and 1842. Through participation in meetings and symposia hosted by tribes and Tribal partners such as Lac Courte Oreilles Ojibwe University, we have strengthened our relationships and capacities to support the diverse and intersectional goals of Ojibwe Nations and their communities. The work presented in this paper is one component of the larger consortium effort.

Through co-design and co-development of technological solutions for data collection, our non-Ojibwe team members learned and refined our understanding of the consequences of privileging Western approaches to conservation science, which often clash with Indigenous methods and ways of knowing [55]. A broader goal of this work includes building processes for proper collaborative engagement that respects Tribal sovereignty and supports data sovereignty. Indigenous Nations and communities often have

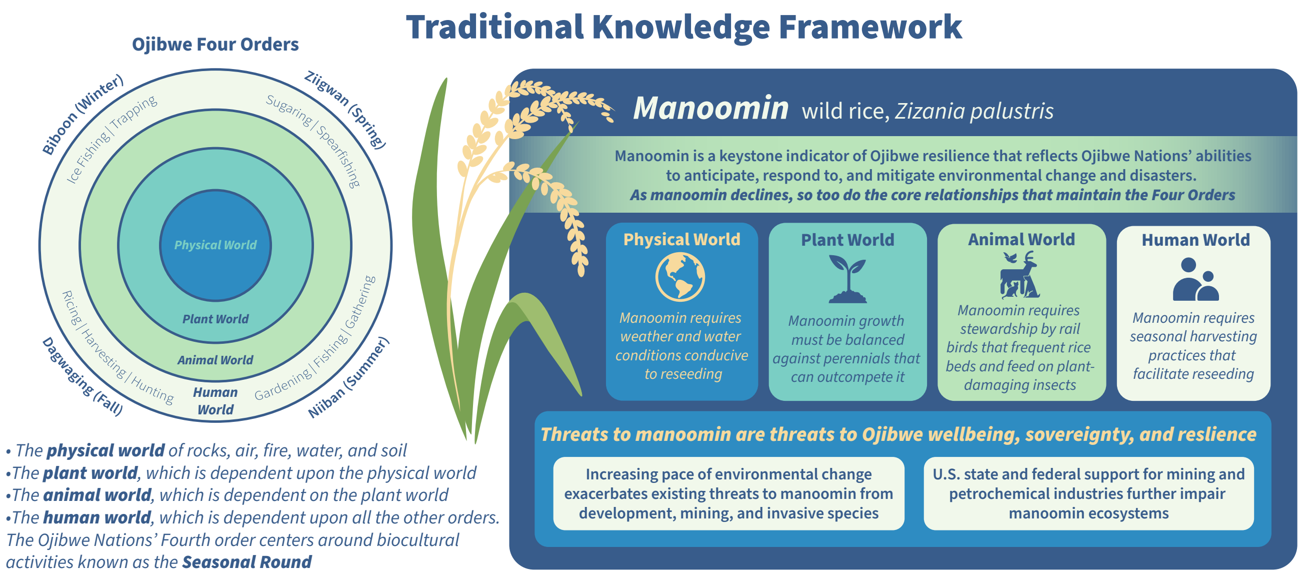


Figure 2: Indigenous knowledge framework regarding Manoomin and its centrality to Ojibwe culture, sustenance, and traditions. The Ojibwe four orders of creation, physical, plant, animal, and human world, all have interdependencies with Manoomin and each other. When going about Manoomin-focused research, these connections must be recognized and respected. *Visual developed in collaboration with and from knowledge shared by Ojibwe Elders Defoe and Leoso [16], partially reproduced with permission from [34].*

norms, value systems, and practices that are not familiar to academic communities. For example, gatherings often revolve around food, prioritize community relationships, and include teachings and cultural traditions such as talking circles. These practices are as, if not more, important for understanding the complex dynamics of environmental change as scientific efforts. It is through such gatherings that Elders and community members generate and share knowledge, observations, hopes, and goals. Because academic researchers often approach Indigenous nations, communities, and peoples as sources of data and knowledge, they typically extract data without recognition of or respect for the rights and needs of the peoples from whom they are taking data. These colonial legacies and their continuation have led many Indigenous communities to deeply distrust academic researchers. In recent years, Indigenous research governance and data sovereignty efforts led by Indigenous scholars and practitioners have gained momentum [6, 60]. These practices support data governance and research protocols that uphold and strengthen Indigenous sovereignty and self-determination.

To advance our process-building goals, we began a long process of establishing data sovereignty protocols and Memorandums of Understanding between Northwestern University and Tribal partners. In 2023, the university general counsel approved the first MOU between the university and Lac du Flambeau Band of Lake Superior Chippewa Indians, and this was signed by a university representative and LDF's Tribal chairman. In this process, we described governance mechanisms for collaborative engagement that respect Tribal sovereignty, provided ways we go about publishing data and papers, and discussed data management and sovereignty practices – protocols which we borrowed and adapted from other collaborations in the region [36] as well as the CARE and FAIR principles applied to Indigenous Data Sovereignty [6].

A major goal of our research efforts is to support Tribal sovereignty and its definition among Tribal communities is worth discussion. Its meaning varies by context, such as legal, political, and identity and is rooted in colonial rule. However, Indigenous Nations have recently tied sovereignty to decolonization and strengthening the ancestral values of Indigenous groups [11]. By leveraging research collaborations to support Tribal Nations and communities in their long-term environmental conservation efforts, Tribal agencies, colleges, and organizations can continue to develop their capacities to lead and implement their science agendas, therewith strengthening sovereignty and self-determination. In the near-term, we aim to support sovereignty and self-determination by sharing our experiences and knowledge with academic and policy communities in the hope of supporting similar efforts.

In accordance with our data sovereignty protocols, we do not share specific locations of deployed sensors on ceded territories and on Ojibwe reservations. We also do not share any data from Ojibwe reservations. The data we do share was collected on ceded (off-reservation) territories. We have received permission from our partners to share this work, and they retain the final say in what is made available to the public. The work presented here offers an incremental, early-stage examination of our collaborative processes and co-design efforts. With future deployments, data, and analyses, we anticipate additional findings that we will share through various publications and other outputs co-authored with Tribal partners.

2.2 Positionality Statement

Collectively, the authors of this paper have male and female gender identities and ethnically identify as white, southeast Asian, Latina, Ojibwe, and Native Hawaiian. The authors include: (1) Tribal natural resource department staff members who work day to day on Manoomin conservation, some who have done so for decades, (2) academic researchers at universities in the USA who are predominantly situated in computer science and engineering disciplines with experience in sustainability and ecological field work, and (3) members of scientific organizations tasked with providing Tribes with natural resource management expertise, legal and policy analysis, and other services in support of the exercise of treaty rights. The authors include enrolled Tribal members who have deep personal, cultural, and ancestral connections to Manoomin. This expertise, alongside more academic expertise in computer and information sciences, shape our teams' positionality and viewpoint.

3 Related Work

This work builds on and contributes to three main research areas – broad and transdisciplinary scientific Manoomin research, asset-based design literature, and HCI works on ecological-focused technologies [30, 31], especially their integration and co-design with Indigenous peoples and respect of Indigenous sovereignty [38, 40].

3.1 Manoomin Research

Despite the extensive research noting the importance of Manoomin for Indigenous Tribes, there are few dedicated deployments of custom sensor efforts documented by the broader academic community [50]. The primary text for understanding Manoomin and its lifecycle is likely by David et al [15], an ecologist who worked for decades at Great Lakes Indian Fish and Wildlife Commission (GLIFWC) providing expertise on the topic. Most Manoomin research is published as technical reports by the various agencies that inform conservation. Hosterman et al. [24] describe and characterize the Lake Superior Manoomin ecosystem and its intersection with culture in a collaborative effort across many tribes and other organizations. Other sharings are in the form of workshop reports and summaries where participants reviewed recent data collections across government agencies and defined action items and needs [48]. Additionally, other mechanisms include descriptions of data sets and data campaigns of Manoomin, which are made available on National Oceanic and Atmospheric Administration's (NOAA) Digital Coast website for use by Tribes and Tribal-affiliated organizations [44]. Beyond these efforts, significant works describing how Manoomin interacts with the surrounding environment, development, and climatic changes are underway [37, 41]. Each of these works informs our study by guiding our sensor design with context about the Manoomin ecosystem.

Another body of scientific research about Manoomin focuses on its cultivation and stems from prior extractive research practices [61]. Many recent initiatives to monitor Manoomin for conservation utilize remote sensing techniques [1], laboratory analyses of physical samples [59], and costly hardware [22], making it difficult to gather continuous, hyperlocal data from hundreds of Manoomin beds across large geographic areas. Additionally, previously deployed sensing devices were generally located on shores near Manoomin beds rather than within the beds themselves [22], limiting data granularity and insight. Finally, a number of social scientific efforts have been conducted on Manoomin harvesters (Tribal and non-Tribal) to allow for monitoring of harvesting practices over time [14]. These community surveys give broader information about challenges with Manoomin and guide our work.

3.2 Low-Cost Co-Designed Microclimate Sensors

Sensor networks have long offered a low(er)-cost alternative to manual monitoring of ecosystems for the past three decades, including seminal deployments on Great Duck Island, Maine in 2000 around the burrows of nesting Leach's Storm Petrels [32], tracking Zebras with collars in Kenya in 2001 [27], and many other applications [51]. Notable surveys for agricultural sensor networks [25], water monitoring [49], and specifically low-cost environmental sensor networks [33] describe how technology advancement drives costs down, thereby increasing capability and applicability.

Previous large-scale research initiatives such as Eclipse [13] and Array of Things [8] are especially relevant to this work. Eclipse was a large Microsoft Research-supported project that designed battery-powered sensors for hyperlocal environmental sensing, specifically air quality monitoring in cities. Researcher-community partnerships deployed over 100 nodes on bus shelters across Chicago, and web tools shared data with the public to provide visualizations and gain insights from the Eclipse Platform. The research team collaborated closely with diverse stakeholders, including policymakers, community organizations, scientists, and residents, to enable the collection of data that provided value. Similarly, the Array-of-Things, a National Science Foundation-supported infrastructure project, deployed more complex devices (akin to NVIDIA Jetson) with wired connections on telephone poles for large-scale city monitoring applications– for example, traffic and congestion monitoring. Other projects include the Intelligent River project [19] in South Carolina, USA and SmartCoast in the EU [46]– both larger scale, more expensive sensor network infrastructure deployments that are general-purpose instruments for regional scientists.

Compared to our work, each of these prior works intends to provide general-purpose solutions to large communities, usually cities. Although some are more closely designed with community members (i.e., Eclipse), they do not integrate Indigenous approaches or engage specifically with Tribes– a key aspect of our work and co-design. Additionally, our work focuses on rural, unconnected, waterborne, and battery-powered low-cost sensing, distinct from the prior work and presenting unique challenges and opportunities.

3.3 Co-design/Asset-based Design with Indigenous and Rural Partners

As with these prior efforts, we also drew inspiration from asset-based design [10, 63], recognizing and celebrating the unique local knowledge and resources that our partner communities possess. This asset-based design mindset directs both the processes– design, deployment, data collection, and analysis– and the outcomes towards usable, impactful levers (i.e., policy briefs, resource management strategies, Tribal priorities).

This work shares common themes and approaches with technology design work in low and middle-income countries. NkhukuProbe [23] developed sensing systems for poultry farming support in Malawi and followed a similar approach as ours, including partner interviews, asset assessment, pilot deployments, and retrospective analyses to iteratively refine a useful tool. Similarly, [62] and [45] explore the challenges and opportunities when involving local partners (in these cases, farmers) in technology production and decision-making.

Finally, we build heavily on prior research from those who worked closely with Tribal partners to develop technological and data-driven solutions. For example, The Full Circle Framework is highly relevant to our work in both approach and associated experience [18]. This work was conducted in northern New Mexico to extend last-mile Internet connectivity via the deployment of television white space (TVWS) wireless technologies. The goal was to provide Internet access to member communities, which included four sovereign Native nations and several rural and semi-urban municipalities and counties. The Full Circle Framework is a "feminist participatory approach for discerning digital inequities through system design in communities with relatively autonomous cultural values and governance practices, including Tribal sovereignty" [18]. The authors noted similar observations to ours that projects "move at the speed of trust" [12] and that projects have to integrate into Tribal government workflows, be responsive to the needs and responsibilities of overworked partners, and be deliberate about data and privacy. Similarly, our work is heavily grounded in prior research focusing on *Indigenous data governance* [7] and *Indigenous data sovereignty* [28, 60], principles that have been crafted by Indigenous communities and non-Indigenous allies. These principles have been primarily developed to address the historical exploitation in collecting and using Indigenous data [60] and to ensure that Indigenous communities can protect data that are sacred to them, which can often be at odds with research initiatives for open data [5]. Thus, researchers, organizations, and Indigenous communities have collaborated to develop principles such as CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics) [5] to provide data sovereignty and governance for Indigenous Peoples. We draw deeply from these and other principles in our work and continue to reflect on how our experiences may contribute to CARE and other principles and frameworks in the future.

Each of these prior works, despite the varied technological interventions, informs our approach. We differentiate between these and our work based on our specific technology intervention (buoy-based environmental sensors) and co-design for the sensing hardware, deployment locations, and data visualizations.

4 System Co-Design around Manoomin

Acquiring continuous, targeted, and quantitative data that explains the decline of Manoomin is a key component of Tribal nations advancing policy change with state and federal government entities who are co-managers of ceded territories. Until recently, many settler government institutions have failed to recognize Tribal co-management and sovereignty despite legally-binding treaties that guarantee such protections. These data-informed policies are integral in protecting Tribal lands from lasting negative influences of outside human and environmental factors and in asserting sovereignty. Although commercial-grade sensors provide high-accuracy data to support Manoomin research, Tribal sovereignty, and conservation management, the cost of these sensors can be several thousands of dollars, which is prohibitive for most Tribal communities. The cost is especially compounded when considering the spatial density that may be desired for Manoomin data collection given the thousands of lakes and rivers in the study area.

We followed a co-design process for Makak using a hybrid of Design Thinking [53] and Assets-Based Design [64] approaches, centering users' knowledge and experience to design a readily fieldable system. The target user population is natural resource managers and other decision makers within Tribal leadership structures. The entire process and its timing are depicted in Fig. 4 We spent the spring and summer of 2023 working with partners to understand their goals, which drove the requirements of the eventual system. We took a two-fold approach to this process by: (1) conducting qualitative interviews to understand the technological challenges and opportunities of field science, distilled in [21]; and (2) engaging with Manoomin knowledge holders through shadowing site-based work, talking with natural resource department leaders, and attending conferences to ensure that our system would be useful to our partners. One exemplary instance of this engagement took place when one author was invited to attend a Tribal Wild Rice Committee meeting to learn about the community's sensing priorities. The author presented a hypothetical preliminary sensing system, communicated trade-offs between different technical approaches, and solicited feedback on the preliminary system, which had been derived from discussions with Tribal members during the prior two months. The 16-person audience was composed of staff from Tribal natural resource departments, Tribal elders, and wild rice chiefs. This discussion converged on a system to collect data about phenomena known by partners to diminish wild rice populations but not yet widely quantified.

Knowledge of these phenomena come from partners' firsthand observations, Indigenous knowledge (often referred to as traditional ecological knowledge, or TEK), rice harvest records, and ecological field work. Such phenomena include (1) brown spot disease, which is related to humidity, precipitation, and abnormal wind gusts; (2) herbivory, for example from geese and swans consuming immature rice stalks; (3) large boat wakes during the floating leaf lifecycle stage; (4) water level, which can change rapidly due to precipitation and landscape modifications, such as beaver dams; (5) sulfate, due to leaching from tailings ponds of nearby mines; and (6) water flow rate. Partners were interested in a sensor that would play a role in both measuring these phenomena and mitigating them, for example by adding an actuator that would deter nearby geese. In addition to sensing modalities, partners provided input on the aesthetics and data retrieval methods of the system. This knowledge sharing was crucial to our understanding of the threats to Manoomin and current efforts to protect it.

4.1 Pilot Goals

To promote an iterative design process, the pilot device targeted a subset of the sensing modalities desired by partners. The device collected standard environmental data at the deployment site: air

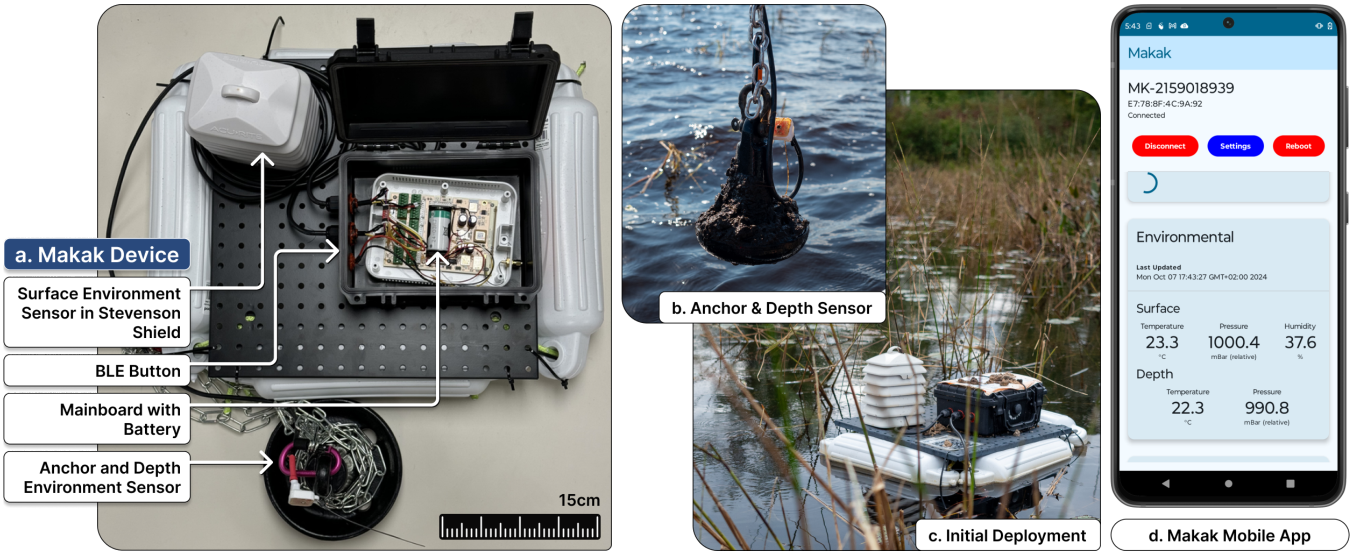


Figure 3: Makak Device: (a) Details of Makak mechanicals and hardware. (b) Image of anchor and depth sensor in a 3D-printed enclosure. (c) Image of a Makak device surrounded by Manoomin at the end of the pilot deployment. (d) A screenshot of the mobile application which helps in validation of Makak sensors and cellular connectivity on-site using Bluetooth Low Energy (BLE).

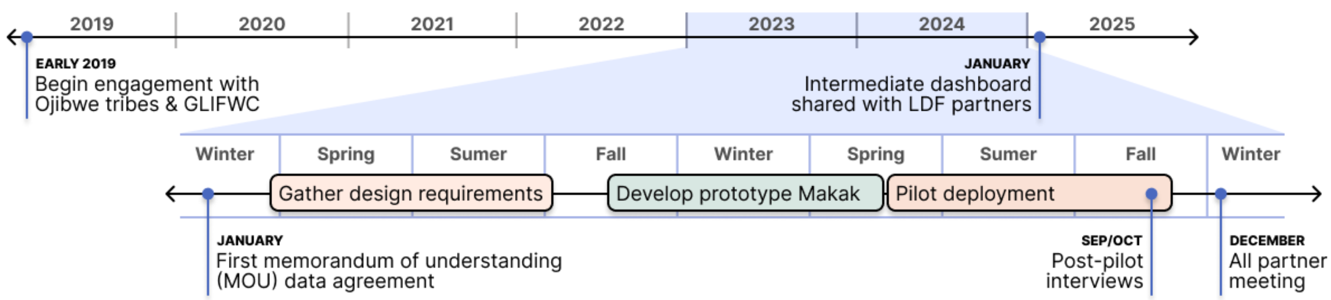


Figure 4: A timeline showing the steps taken for the Makak relationship building, co-design, deployment, and evaluation processes.

temperature, water temperature, humidity, and water depth in a low-cost, easy-to-deploy, and continuous manner. We and our partners also wanted to begin understanding mechanical disturbances to the rice beds, specifically for water movement due to boat wake and wind. Characterizing boat wake via low-cost sensors remains an open research question and requires more data and testing to identify sensing and signal processing solutions.

To collect relevant microclimate data, we set a goal for the device to be deployable directly in wild rice beds. To minimize the burden on users and potential disturbance to a rice bed, it had to last the entire growing season, roughly April through September, and report data wirelessly. To ensure that budget-constrained users could afford to adopt and deploy the device, these devices must also be low-cost. We spoke with partners about their budgets and the costs of similar sensing systems they used or considered using, determining that our device should cost under 1000 US Dollars. Research grants at our academic institutions provided the funding for the development and testing of the pilot device. We prioritized development of the system to collect data in time for the 2024 Manoomin season, which began in the spring after lakes and rivers thawed. To facilitate refinement and iterative development based on the first season's operation, we understood that feedback collected from this Manoomin season would likely motivate large future design changes.

4.2 Technical Design

4.2.1 Electronic Hardware. The pilot device used Hardwario's Chester-M[4] as the basis of the sensor design. Hardwario provides a system with generalized capabilities for sensor interfaces, power, and wireless communication without any proprietary firmware or software. Chester-M includes a Bluetooth enabled microcontroller, modems for Long Range Wide Area Network (LoRAWAN)

[4]https://www.hardwario.com/chester

and LTE-M cellular (a low-power networking standard designed for machine-to-machine communication), an inertial measurement unit (IMU), and breakouts for I2C interfaces. For power, we used a 7700mAh 3.6V Lithium Thionyl Chloride battery, which is well suited for a wide temperature range to span the full Manoomin season from spring ice melt through autumn harvest. We used two external sensors: a BME280 (Bosch Sensortec) environmental sensor for the surface measuring temperature, air pressure, and humidity, and an MS5803 (TE Connectivity) underwater temperature and water pressure with custom waterproofing.

4.2.2 Software. The device ran the Zephyr real-time operating system to initiate scheduled tasks for taking environmental readings, recording acceleration events, and sending data over the cellular network, with data buffered in internal flash storage between cellular requests. We collected temperature and humidity directly from sensors and calculated relative water depth using the difference of two pressure readings, one above water surface (air), and one at a fixed point on the anchor (water). We captured indications of movement for wave action (boat wake) using the IMU, recording the strongest frequencies identified using a Fast Fourier transform. We also implemented a Bluetooth mode that could be activated via a button on the case, allowing for live validation and updates through a smartphone app.

4.2.3 Mechanicals. The device assembly was composed of a platform kept afloat by four boat fenders. The platform held the surface environmental sensor in a Stevenson screen and a waterproof case that housed the Chester-M board. A chain and cable connected the underside of the platform to the anchor and depth environmental sensor. We enclosed the depth sensor in a custom 3D printed case that sealed the electronics in epoxy while exposing the waterproof sensor.

5 Makak Pilot Field Deployments

Before deployment, Kathleen Smith (GLIFWC) named our Manoomin microclimate sensor *Makak* after discussing with her Ojibwe language teacher, Howard Kimewon. In Ojibwe, Makak means "a semi-rigid or rigid container: a basket (especially one of birch bark), a box"[5]. We introduced Makak to the broader community in the Niibin (Summer) 2024 edition of Mazina'igan published by GLIFWC [20].

5.1 Deployment Locations

We deployed two Makak devices each with GLIFWC, 1854TA, and LDF in late April 2024 and LCO in late May (see Fig. 5). Partners identified specific deployment locations in areas with interesting or diverse Manoomin beds, also considering ease of site access for possible maintenance during the pilot deployment.

5.2 Deployment Protocol

Before each deployment, we met with members of the corresponding partner organization responsible for Manoomin management and gave a brief presentation of the sensor and deployment protocol. Fig. 5 provides information on location, partner, data measurement, status, and notes for each of the eight Makak devices. We retrieved six of the devices in September 2024 and the remaining two in October 2024. During each field visit, a local partner accompanied us and we each made an offering of *Asemaa* (tobacco) as is customary with Ojibwe traditions in reciprocity with *Nibi* (water) [29].

At each deployment location we recorded initial sensor readings, network status information, hardware identifiers, GPS location, and ground truth values of water depth (using a measuring tape), along with unstructured field notes. We adjusted the platform-to-anchor chain length based on partner insight into maximum water levels at that location (and observations while on-site in the water), and secured flat metal sheets to anchors in locations with particularly mucky bottoms to increase surface area. Once we deployed the nodes, we verified BLE functionality through the smartphone app and ensured that our accompanying partner could access the app independently.

5.3 Deployment Results

Figure 5 shows high level metrics regarding our deployed Makaks. Notably, six of eight devices collected usable data, but Makaks 5 and 6 were unable to connect to the LTE-M network at all. These two devices were left in the field solely for mechanical validation as there was no immediate remediation to cellular connection issues. However, connectivity on Tribal land is a focus for future deployments. Makak 8, which was also on a reservation, showed connection inconsistencies, and would only periodically send data to the cloud.

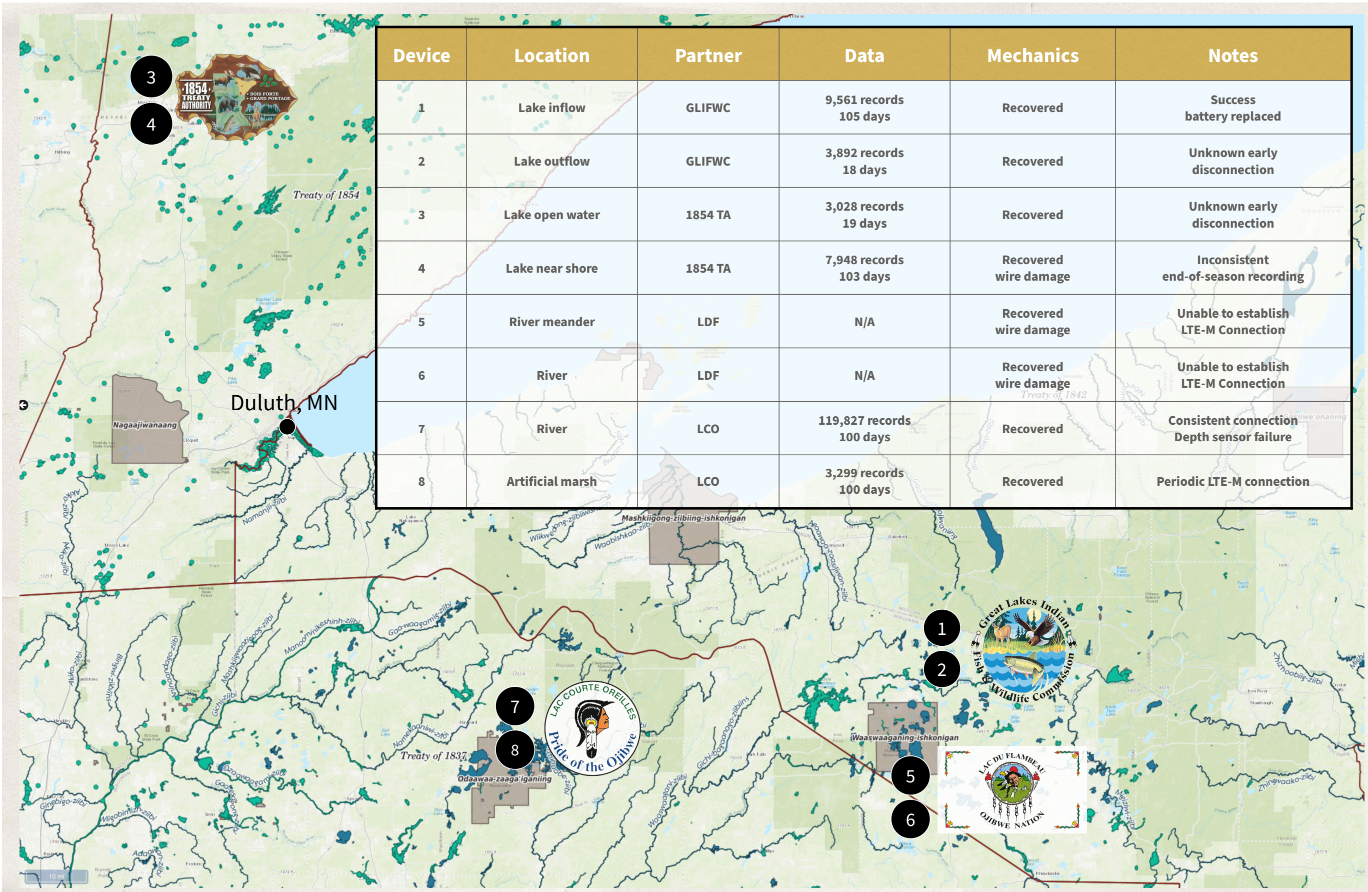
Makaks 2 and 3 stopped recording data after 18-19 days for unknown reasons, but because both devices each had another device deployed on the same water body (Makaks 1 and 4, respectively), and because many of the devices are in remote locations that require significant time and coordination to reach, we decided not to intervene immediately.

On a planned trip (not directly related to the deployment), we revisited Makaks 1 and 2 in early August and replaced Makak 1's battery after initially lasting about 72 days. However, we could not find Makak 2 due to dense Manoomin growth so could not replace its battery.

Finally, Makak 7 had issues receiving remote parameter updates from our cloud system. Thus, it collected data much more frequently than the other devices, as it was stuck on the setting used during deployment to quickly validate while in the field. Makak 7 continued to record this higher frequency for its entire deployment. It is unknown why this issue occurred, but it provided helpful data for battery life validation in showing that the batteries could support high temporal resolution data collection for extending periods of time.

The Makak mechanicals generally performed well. We retrieved all eight devices from their original deployment location. A few devices suffered damage, with a least three devices having individual sensors fail. Several sensors also exhibited signs of wildlife interaction, either via damaged cables and/or excrement and nesting on the platforms, as seen in Figure 6b and 6c. Makak 4 started showing erratic water pressure readings near the end of deployment due to completely severed cables running to the underwater sensor. Additionally, an unknown outside actor attached pink ribbon and flags to the devices deployed with 1854TA, as shown in Fig. 6a, indicating

[5] https://ojibwe.lib.umn.edu



Device	Location	Partner	Data	Mechanics	Notes
1	Lake inflow	GLIFWC	9,561 records 105 days	Recovered	Success battery replaced
2	Lake outflow	GLIFWC	3,892 records 18 days	Recovered	Unknown early disconnection
3	Lake open water	1854 TA	3,028 records 19 days	Recovered	Unknown early disconnection
4	Lake near shore	1854 TA	7,948 records 103 days	Recovered wire damage	Inconsistent end-of-season recording
5	River meander	LDF	N/A	Recovered wire damage	Unable to establish LTE-M Connection
6	River	LDF	N/A	Recovered wire damage	Unable to establish LTE-M Connection
7	River	LCO	119,827 records 100 days	Recovered	Consistent connection Depth sensor failure
8	Artificial marsh	LCO	3,299 records 100 days	Recovered	Periodic LTE-M connection

Figure 5: Map of the deployment region with general indications of deployment areas. The table show high level deployment details and result for each Makak device. The dark green shading indicates active rice lakes (https://maps.glifwc.org).

that the devices had not been visible enough as designed. We later discovered the ribbons were attached by members of Minnesota DNR, in an effort to make the devices visible to boaters.

Each device sent its data over the cellular network and stored it in Hardwario's cloud application. Here we highlight some initial findings related to device design and operation, but we will continue to iterate on data collection and analysis over the next development cycle. First, the surface and depth sensor correlate well ($p < 0.0001$ between all reporting sensors) and track a difference consistent with seasonal weather patterns, showing promising results for using this method to measure relative water depth. We deployed two sets of devices (Makaks 1 and 2, 3 and 4) on the same water body; both show significant correlation in surface to depth pressure ($p < 0.001$). We compared Makak 7 with a reference water level sensor sensor deployed by 1854TA (Global Water Instrumentation WL16U-015), which showed significant correlation ($p < 0.00001$, $r = 0.88$), as seen in Fig. 7b. Surface and depth temperature readings also correlate well ($p < 0.01$ for all reporting sensors), showing strong diurnal variation (24 hour auto-correlation mean- surface: 0.61, depth: 0.55 for reporting sensors, $p < 0.0001$), as shown in Fig. 7a. We hypothesize the weaker correlation in depth was because of higher thermal capacity of water versus air temperature. Humidity was less immediately useful - although diurnal variations are visible in the data (auto-correlation mean 0.39, $p < 0.0001$), the sensor often tops out at 100% humidity. We hypothesize this is because condensation causes an extremely humid environment inside the Stevenson screen enclosure. Finally, acceleration events showed indications of device movement. However, we need further analysis and exploration to determine whether acceleration events are tied to boat wake, wind, or other phenomena. This will be tackled in future controlled experiments using wave generating lab equipment, and could be verified in the field via co-deployment with cameras for ground truth.

5.4 Post Deployment Interviews

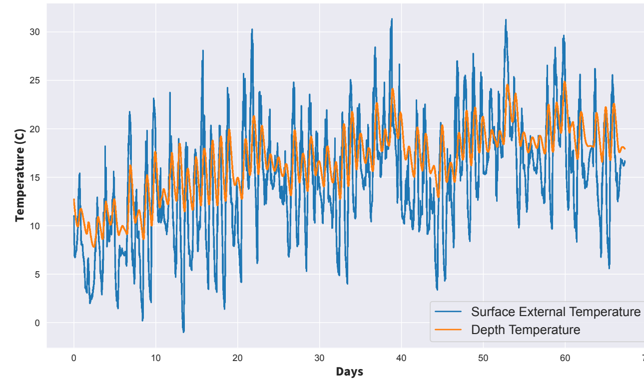
5.4.1 Methodology. In accordance with our IRB protocol, at the end of the roughly four month pilot deployment in September and October 2024, we conducted semi-structured interviews onsite with partner organizations. The interviews aimed to solicit feedback on the device development and deployment process as well as inform continued device development and refinement. We conducted four interviews, each with 1-2 Manoomin management representatives from the partner organization, and lasting between 30 and 90 minutes.

(a)

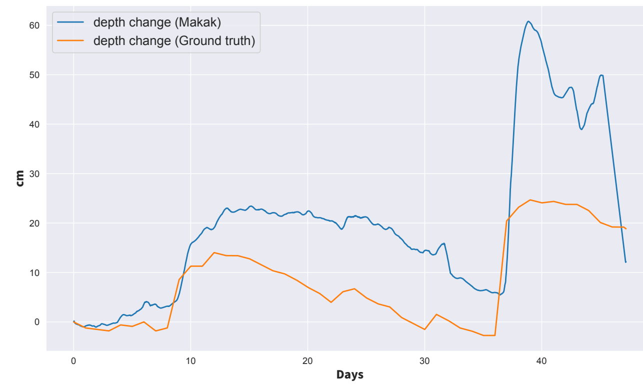
(b)

(c)

Figure 6: Makak deployments upon retrieval. (a) A Pink ribbon has been placed on the sensor by Minnesota DNR for better visibility in open water, and the depth cable has been severed. (b) Damage to exposed cable. (c) Nesting found under the sensor's floating platform.



(a) Temperature variation



(b) Relative water depth v. surface elevation

Figure 7: (a) Surface (air) and depth (water) temperature from device 2 deployed with the Great Lake Indian Fish and Wildlife Commission (GLIFWC). Diurnal variations in both signals can be seen, however water temperature fluctuations are less extreme due to heat capacitance. (b) Device 7 deployed with 1854 Treaty Authority showing centimeter change compared to a co-deployed water surface elevation device. The pressure signal shows significant correlation to the elevation which is promising, but requires more analysis to understand drift.

The interviews began with an informal, conversational walk-through of slides we made to review details about the Makak pilot study and share data plots from the two devices deployed at that partner location over the summer [6], such as those shown in Fig. 7. We encouraged questions and comments during the slideshow then used leading questions to encourage partners to share their thoughts about the successes, challenges, and future of the project, (i.e., What are anticipated challenges with future deployments?).

With participant consent, we audio recorded each interview and transcribed it using otter.ai. We analyzed the data to identify

[6]except at LDF where the devices could not establish a cellular connection and data from a nearby partner location were shown instead

common themes and targeted feedback that could inform ongoing Makak planning and development.

5.4.2 Interview Results. Overall, the partner interviews revealed positive feelings about the Makak pilot deployment, with one partner noting that it "seemed like a really, pretty successful first run" and another stating "I think for a prototype, it definitely, I would call it successful". We acknowledge the limitations of critiquing a system in which both the interviewers and interviewees had invested much time and effort. Co-design research has identified that partners can "provide polite responses" to preserve the relationship rather than giving critical feedback [9]. However, we relied on the strength of our long-term relationships, transparency in discussing challenges and shortcomings in the past (i.e., having to shift deployment schedules for additional engineering time), and aligned goals of Manoomin protection to have productive conversations. It was encouraging that all partners provided constructive feedback, for example about improving the ways that data are accessible and visualized, indicating that our partners felt comfortable being critical of the system at least to some degree.

Drawing from their knowledge and expertise, several partners explained variances and anomalies in the data, for example, pointing to large storms on dates that corresponded to drastic changes in water levels. Partner organizations held differing views about the necessity of certain sensors, such as those for wave detection or humidity, at their specific sites. However, all remarked that having these data available to them – and especially from larger deployments – would be helpful "to pull out patterns that might correspond to harvest". Additionally, partners were all eager to have data from additional sensing modalities and over longer periods of time, with one partner noting "this is powerful data like, we're all like, wow, I want more. I want more". Although partners did not always immediately recognize *how* they would use certain data, the general feeling was that having the data would enable action around tasks such as Manoomin management, policy making, and implementing local regulations.

Partners also revealed important considerations for the planned deployments during future summers, both by noting new, helpful sensing modalities and highlighting user interface areas that may need extra focus. For example, in discussing the potential of Tribal members and partners deploying Makak devices themselves, one partner noted that the main challenge would be the ease of installation "especially if us lay people are installing these things".

Despite the challenges we faced in the pilot deployment, partners were understanding and supportive, recognizing that "whenever you use field data or applied data, or applied science, to collect data, there's always going to be a field quirk." Furthermore, the partners all expressed optimism about the future iterations of the device, the forward progress of the project, and the ongoing commitment of the research team. In particular, one partner noted "This is great that you're working through it. So it's not like 'we tried, too bad', but you're still, you're going to make it happen like working through and that has huge benefits for this and others." These results point to the success of our relationship-building efforts and reiterate the time necessary to develop trustworthy collaborations with non-research communities and work at the pace of trust.

5.5 Post-analysis Meeting with all Partners

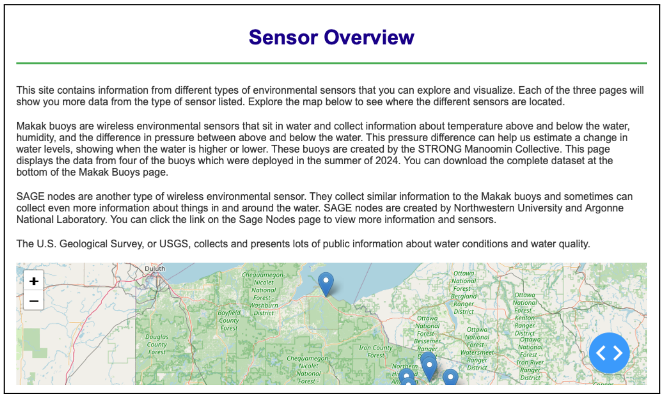
During the post deployment interviews, some partners recommended a group meeting with the research team and all partner organizations, an idea we had not previously considered. We held this meeting online in December 2024 with participation from four members of the research team and 1-3 representatives from each of the four partner organizations. In the meeting we gathered feedback from partners about the pilot deployment then shared plans for the second version of Makak to be deployed in summer 2025 and provided partners opportunity to respond to the plans.

This session gave all partners the opportunity to discuss together, echoing successes, challenges, and future ideas. A key point of collaborative discussion included suggestions to improve the visibility and awareness of Makak sensors when deployed, for example by including informational material about the project at boat launch locations. Additionally, this meeting allowed us to present and discuss new sensing modalities as a larger group. Audio and light sensing had been discussed in one post-deployment interview, but not shared among all partners. Overall the feedback was positive regard the plans for next iteration of the sensor. However, during the meeting, partners commonly reported issues accessing the Makak data. Several explained that they had forgotten how to find the data and would prefer an easier entry point, such as a web app. Additionally, partners noted difficulty in *interpreting* the Makak data, with one partner stating "it was kinda hard when I did see the data, at least that initial time, to know what I was seeing". These remarks point to the need for a more easily-accessible, streamlined data platform.

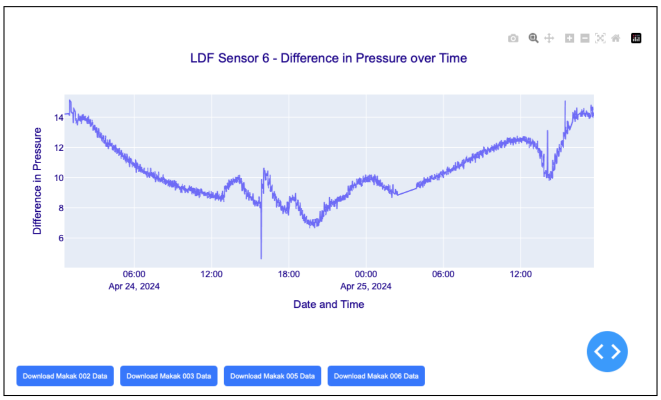
5.6 Dashboard

Part of our larger research initiative is to establish an interactive public dashboard so that partners and broader audiences can access, interpret, and download historical and real-time data about Manoomin, including data from the Makak devices. While this larger research dashboard is in progress, partners at LDF expressed interest in having an intermediate, smaller dashboard - specifically to explore data collected within or near the Lac du Flambeau Nation. LDF partners were interested in viewing the 2024 Makak season data and other comparable public environmental data streams, such as USGS streamflow data. Partners noted that this smaller dashboard would be especially useful for facilitating community workshops about the sensors and getting a broader audience engaged in Manoomin conservation. Furthermore, this dashboard would allow partners to begin exploring how the Makak data could be useful for Manoomin monitoring based on the growth and yields experienced and how they relate to Makak and other environmental data.

Thus, we developed a temporary "LDF dashboard", as shown in Fig. 8. In accordance with our MOUs and data sovereignty protocols, this localized dashboard is password-protected because it contains data that are not publicly available per the terms of our MOU agreements. The central aspect of the LDF dashboard is that users can access interactive graphs of Makak data for temperature, humidity, and the difference between surface air pressure and anchor water pressure. It also contains graphs from and links to two public sources for additional environmental monitoring platforms [52, 58]. The home page contains a map of sensor locations



(a)



(b)

Figure 8: The LDF temporary sensor dashboard. (a) the home page of the dashboard, with descriptor text and a map of sensor locations. (b) An example graph from the Makak sensor showing the difference in air and water pressure.

and descriptions of the different sensing modalities. Users can also download complete 2024 Makak device data in CSV format. The dashboard is intentionally simple and functions as a temporary, user-friendly data access solution to ensure data are usable in the near-term while a larger and more formal solution is crafted.

In a feedback session about the LDF dashboard, partners commented that it was a "good visual aid" that provided "more access", "convenience", "ease", and "accessibility" for exploring data. Partners noted that the dashboard also supports data sovereignty by allowing Native nations to collect, store, and analyze their own data over long periods of time. Partners shared valuable suggestions for improving the dashboard, such as situating real-time and historic data side by side and adding more pictures and diagrams of the sensors. As one partner concluded, this dashboard can be "a Walmart dashboard", referring to its conveniences as a "one stop shop" for data access. This feedback session demonstrated the value of having the "toolbox" infrastructure for Native nations to enact sovereignty through data access and sharing.

6 Discussion

As part of our iterative co-design process and continued relationship building, we conducted a retrospective of the Makak co-design and pilot field deployment. The goal was to understand lessons learned and framing for our future work. Additionally, we aimed to provide insights for other researchers who may work with Indigenous scientists and partners and on Indigenous lands. We present takeaways and lessons below combining our learning from partners, data, and deployment mechanicals.

6.1 Broader Takeaways

Despite the small size of our pilot deployment and limited data collected, our results point to broader takeaways that are applicable to our future work and for other researchers working on technology with Indigenous partners and low-cost environmental sensing. We further describe those takeaways in this section.

6.1.1 Promise of Co-Designed Sensing Systems. Through our work, we saw first-hand that taking the long, slow process to design sensing systems *with* partners provides benefits for researchers and community partners. By investing time to observe and learn from partners, we gained knowledge about the Manoomin life cycle and threats and developed tailored sensing systems to monitor a number of these threats. Working with partners to identify deployment locations allowed for the elevation of local knowledge and expertise. As with prior work [13], we found that deferring to local knowledge revealed areas of concern that were not apparent to the research team. Reviewing Makak data with partners highlighted concerns around data privacy and visualization, pointing to future work initiatives to ensure that the data are both useful and respectful. In summary, we found that co-designing several aspects of the Makak system helped to elevate local and Indigenous knowledge, build trust between researchers and Tribal partners, and allow for the project to be implemented "in a good way."

6.1.2 Utility of Low-Cost Microclimate Sensors. We found through our pilot deployment that despite their inaccuracies, low-cost microclimate sensors can provide utility in tracking patterns and changes over time. As seen in Fig. 7a, the Makak sensors are *precise*, as they correlate well with each other when deployed in the same body of water. Although the sensors are not accurate in terms of exact values, as seen when compared to a commercial-grade sensor in Fig. 7b, the sensors capture trends and patterns well. This is further reflected by our partners noting large storms and other events that link to the sensor data. Thus, we determine that low-cost microclimate sensors for water temperature, water level changes, and acceleration events provide useful information about changes that occur in the environment.

6.1.3 Potential Impact of Makak Data. Because Manoomin is sacred to the Ojibwe people and the factors affecting its health are numerous and complex, gathering any data related to Manoomin health and microclimate is useful for its conservation and preservation. As our partners noted, the data are powerful and they want more. Additionally, despite the challenges partners had in interpreting Makak data, we saw that partners could easily connect their local knowledge to the data. We highlight this finding as an indicator of the potential impact of Makak data, in providing quantitative measures that reinforce and support local knowledge and experience to enable community action. We note, however, that determining which data are most useful will require several seasons of Makak data compared to Manoomin health and yields.

6.2 Team Building and Mentoring

Our team and larger consortium come from diverse cultures, nations, and scientific disciplines. Early on we encountered challenges and made mistakes due to our patchwork approach to onboarding team members and the temporal mismatch between academic and partner timelines and demands, similar to those faced by the Eclipse project [13]. A more rigorous approach, including attendance at Tribal gatherings, the use of stories-of-self, and a shared library of writings from both Western and Indigenous literature is essential to reduce mistakes, broken relationships, or breaches of trust, particularly for academic teams with high turnover (graduation, etc).

6.3 Data Sharing vs. Data Sovereignty

As discussed earlier, one core component of this project is upholding Indigenous sovereignty in part through our commitments to data sovereignty. In contrast to dominant approaches where researchers "share" data with partners and communities, we began our work with the assumption that the Native Nations we work with own and govern the data generated through the project. Whether they share the data is up to them. To enact these commitments, we engaged with significant literature around Indigenous Data Sovereignty [6] that grapples with the history of researchers and academic institutions collecting data from Indigenous Peoples and Native Nations without free, prior, and informed consent and without consideration of the need to share the results of research or return data back to the communities. These ongoing histories of data extraction and theft has led to negative material outcomes for Indigenous Peoples and fomented deep mistrust of researchers and academics. To be effective collaborators in codesign, a research team must be deliberative and intentional to ensure that any data collected, analyzed, and stored adhere to each tribes' data sovereignty laws, regulations, and/or requirements. Although the depth of this topic is beyond the scope of this article, it is a critically important consideration for any project.

6.4 Sturdiness and Durability of Sensors and Indigenous-Centered Approaches

The Western Great Lakes experience environmental extremes, with cold frozen winters and humid summers. Stronger, reinforced cables for external sensors, a non-flat surface to avoid animal interference, and improved visibility would benefit deployments and increase resiliency during field deployments. Because Indigenous structural design is rooted in durability, sustainability, and respect for land [35], seeking Ojibwe artists and artisans to incorporate Ojibwe container designs and materials could deepen our collaboration and make for more resilient sensors.

6.5 Hardware, Firmware, Software, and Connectivity

Although vendor maps indicate LTE-M coverage in our deployment locations, we encountered connectivity issues with some of our devices on Tribal land. Exploring different carriers, signal boosting, and investing in testing equipment early on would help select the best signal carrier and specific deployment location. If LTE-M networks are not available, LoRAWAN or satellite networks are one option (albeit expensive). Larger local storage on device to mitigate intermediate connection loss, ensuring battery life can support the 120 day growth cycle of Manoomin, and integrating solar panels for longevity all provide avenues for more durable and reliable sensing. Finally, engaging in more frequent pre-deployment testing with partners in controlled environments would benefit any future sensor deployment of this type.

6.6 Individual versus Communal Feedback

Our approaches to gathering partner feedback were initially designed in an *individual* manner, in which we met with each partner organization individually then reviewed and analyzed results as a research team. However, one partner organization noted in the post-deployment interview that designs for future data platforms were not up to those members alone, but rather were up to the Tribal community, suggesting the need for *communal* feedback. Similarly, multiple organizations noted the desire for an all-partner meeting to hear from each other and share thoughts as a community. In this way, we found that the typically-used participatory approaches may not apply to Native American populations who are underrepresented in research communities. This aligns with recent research suggesting that new forms of participatory design must be considered for communities who are often underrepresented in research [30].

6.7 Openness to New Directions

Over the course of the deployment season and during post-deployment interviews, partners generated new sensing ideas and recommendations for improving the Makak devices. These suggestions are a welcomed and critical aspect of our partner-driven research and development. Balancing design, functionality, and partner suggestions remains an ongoing goal for our research team. At times, the constraints of technical capabilities and deployment logistics mean that certain suggestions cannot be implemented exactly as partners first envision. Transparency and communication about these trade-offs and limitations is essential. When limitations and goals are clearly outlined and shared, our interdisciplinary team has the flexibility to focus on how the Makak sensors can best protect Manoomin. Having research team members be open to new directions and suggestions from partners – and be willing to become a novice and learn about a new domain [57] – extends the utility of these devices beyond their contributions to the academic field of computer science and instead prioritize the sovereignty and resilience of Indigenous communities.

As examples of things we learned, partners noted: (1) Light sensing at surface and depth could help in gauging sunlight and weather, along with measuring the exposure at depth which can be affected by water staining, debris, or other flora– useful for correlating micro-climate to Manoomin health; (2) Water conductance can serve as a proxy for sulfate levels— partners take samples of water bodies at various times throughout the year, but real-time conductivity could help target important times to sample; (3) Audio recording for wildlife monitoring and herbivory could provide a health metric on Manoomin stands, that are known to hum with bees who gather pollen but do not act as pollinators [15]. All of these directions stem from Tribal priorities– researchers and academics must be open and honest about what is possible in the short and long term, prioritizing together for the most collective benefit.

7 Limitations and Future Work

7.1 Limitations

The pilot study contains eight sensors in carefully chosen locations for ease of access and cellular coverage near Manoomin sites. Further deployments in more diverse and varied environments could reveal more challenges related to connectivity, usability, and overall scalability. This pilot deployment still represents an improvement on partners' standard procedure for collecting environmental data, which is even more manual and limited than the Makak pilot. Additionally, although the pilot devices demonstrated durability to environmental stressors like sun exposure, humidity, and biofouling, some of the external sensors were damaged by these factors and the system needs more extensive evaluation to prove durability in all intended deployment conditions. Using battery power without the ability to recharge also limits the scalability and locations for deployments, as well as increasing the negative environmental impact of longterm deployments. A more extensive array of sensing modalities, such as for pollution monitoring and water quality, would provide additional insight into challenges Manoomin faces, but the chosen array of pilot sensors was selected based on analyses with partners on cost, complexity, and usefulness.

7.2 Future Work

Although the data from these initial deployments provide useful insights for partners, the primary goal of the pilot deployment was to gain insight on and refine our sensing system for future iterations. As the "Lessons Learned" section indicates, these improvements apply not only to technical aspects of the design but also to the collaborative design processes that uphold Tribal data sovereignty. The deployment outlined in this work was a successful proof-of-concept, however much work is needed to mature the system into one that has a scalable impact on Manoomin protection.

Improvements in the next iteration focus on stability, scalability, and data accessibility, in addition to addressing specific shortcomings discovered in the pilot. These improvements serve the primary goal of sustaining data collection for as long as possible throughout the growth season and making the data timely and actionable for partners. Although we had near real-time (1 hour max latency) raw data available via APIs during this pilot deployment, we aim in the next deployment to make near real-time calibrated and processed data available through dashboards and data visualization tools. For example, rather than scrolling through time series data packets and manually subtracting water and air pressure readings to determine water level, partners will be able to view automated graphs and maps that display this information with historical values (with raw data still available as an option). With this improvement, Makak sensors can become integrated into day-to-day Manoomin conservation and management activities. In order to achieve this, we need to build a robust data processing pipeline, rework power management by introducing energy harvesting, and enhance our wireless connectivity to minimize dead zones or intermittent connectivity. Frequent partner engagement will ensure that the data visualization dashboard will align with partner goals and processes. Additionally, we will continue to iterate on the sensing modalities for water depth, temperature, and humidity by evaluating against and calibrating with ground truth commercial sensors. Improvements to the deployment process and simplifying the system assembly will improve scalability, permitting the datasets to grow to new deployment locations.

Makak will also be improved by the addition of new sensing modalities, mentioned in the "Lessons Learned" section, that are of interest to both Tribal Natural Resource Departments and the greater Ojibwe community. Makak's versatility and ease of deployment provide opportunities for experimentation: as new questions arise, it will have the ability to adapt as needed. We plan to incorporate a system for trial sensors which are secondary to the core functionality, ensuring that failures will be localized and not inhibit the overall functionality while successes can be later included in core designs.

Finally, to achieve the long-term goal of sovereignty and collaborative design, access to the system must be broadened to the greater Ojibwe community, both for system design and deployment. We aim to collect data on usability, including ease of deployment, maintenance, and data analysis in our next deployment. This will include trialing deployments with those not involved in system development, collecting associated feedback, and implementing quality-of-life improvements. We must continue considering the environmental impact, educational outreach opportunities, and Indigenous ways of knowing, specifically for instances that Tribal partners advocate.

Outside of contributions specific to Makak, this pilot deployment reveals the benefits of research into sensor accessibility and data visualization, specifically for Tribal communities and other groups with extensive knowledge of their natural environment who have typically been excluded from technology design processes. There is a strong need for social science work exploring data visualization for environmental stewards, particularly for conservation processes that require timely and laborious action. This work also emphasizes that Internet-of-Things research must center long-term engagement with user communities as many of the insights here were only possible through extended collaboration.

8 Conclusion

In this paper, we introduce a co-design effort to protect Manoomin, a naturally growing wild rice that is central to the identity and lifeways of Ojibwe people. With four partner organizations, we designed and deployed a pilot study of Makak, the first wireless, low-cost, microclimate sensor designed to measure the environment of a wild rice bed. The pilot study consisted of eight devices deployed around the Lake Superior region. The deployment had successes and challenges both in co-design and the technical design of the sensor. As a result of this work, we feel well-positioned to continue iteration with our Tribal partners, expand future deployments, and progress the protection of Manoomin in a good way. We share these experiences, challenges, and lessons learned to support other Tribal/academic relationship-building that is reciprocal, respectful, and towards the common cause of a more just and sustainable world.

Acknowledgments

Miigwech (thanks) to our Tribal and Tribal-serving organizational partners who assisted greatly in our fieldwork, site selection, and project scoping. This research was supported by the National Science Foundation through grants RISE-2209226, CMMI-2233912, and CNS-2145584. This research was also partially supported by a graduate fellowship generously funded by the Brook Byers Institute for Sustainable Systems at Georgia Tech. We would also like to acknowledge support by the Alfred P. Sloan Foundation, VMWare, Google, and Catherine M. and James E. Allchin. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or other supporters

References

[1] Mary Banner. 2023. Enbridge Line 3 Impact on Wild Rice Lakes in Minnesota Using GIS and Remote Sensing. *Voices of Indigenuity* (2023).

[2] Anna Belinski. 2023. Minnesota Dep't of Nat. Res. v. Manoomin. *Public Land & Resources Law Review* 22 (2023), 3.

[3] Edward Benton-Banai. 2010. *The Mishomis book: The voice of the Ojibway.* University of Minnesota Press.

[4] Laura Boffi. 2024. Retracing ecological relationships: paving the way in Malaysia. In *Proceedings of the Participatory Design Conference 2024: Situated Actions, Doctoral Colloquium, PDC places, Communities-Volume 3.* 24–26.

[5] Stephanie Russo Carroll, Ibrahim Garba, Oscar L Figueroa-Rodríguez, Jarita Holbrook, Raymond Lovett, Simeon Materechera, Mark Parsons, Kay Raseroka, Desi Rodriguez-Lonebear, Robyn Rowe, et al. 2023. The CARE principles for indigenous data governance. *Open Scholarship Press Curated Volumes: Policy* (2023).

[6] Stephanie Russo Carroll, Edit Herczog, Maui Hudson, Keith Russell, and Shelley Stall. 2021. Operationalizing the CARE and FAIR Principles for Indigenous data futures. *Scientific data* 8, 1 (2021), 108.

[7] Stephanie Russo Carroll, Desi Rodriguez-Lonebear, and Andrew Martinez. 2019. Indigenous data governance: strategies from United States native nations. *Data science journal* 18 (2019), 31.

[8] Charles E. Catlett, Peter H. Beckman, Rajesh Sankaran, and Kate Kusiak Galvin. 2017. Array of things: a scientific research instrument in the public way: platform design and early lessons learned. In *Proceedings of the 2nd International Workshop on Science of Smart City Operations and Platforms Engineering - SCOPE '17*. ACM Press, Pittsburgh, Pennsylvania, 26–33. https://doi.org/10.1145/3063386.3063771

[9] George Hope Chidziwisano. 2024. Overcoming HCI4D User Research Challenges by Combining Diaries and Technology Probes. *International Journal of Human–Computer Interaction* (2024), 1–15.

[10] Alexander Cho, Roxana G Herrera, Luis Chaidez, and Adilene Uriostegui. 2019. The" Comadre" Project: An Asset-Based Design Approach to Connecting Low-Income Latinx Families to Out-of-School Learning Opportunities. In *Proceedings of the 2019 CHI conference on human factors in computing systems.* 1–14.

[11] Amanda J. Cobb. 2005. Understanding Tribal Sovereignty: Definitions, Conceptualizations, and Interpretations. *American Studies* 46, 3/4 (2005), 115–132. https://www.jstor.org/stable/40643893 Publisher: Mid-America American Studies Association.

[12] Stephen MR Covey, Stephen R Covey, and Rebecca R Merrill. 2008. *The speed of trust: The one thing that changes everything.* Simon and schuster.

[13] Madeleine IG Daepp, Alex Cabral, Tiffany M Werner, Raed Mansour, Charlie Catlett, Asta Roseway, Chuck Needham, Nneka Udeagbala, and Scott Counts. 2023. The "Three-Legged Stool": Designing for Equitable City, Community, and Research Partnerships in Urban Environmental Sensing. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems.* 1–19.

[14] Mae A Davenport, Bree Duever, Anna Kadrie, Emily Green, Jaren Peplinski, Laura Matson, Michael Dockry, and Gene-Hua Crystal Ng. 2020. Protecting the Harvest: A survey of Minnesota state-permitted (non-tribal) wild rice harvesters.

[15] P. David et al. 2019. Manoomin. *Great Lakes Indian Fish and Wildlife Commission* 1 (2019), 1–158. Version 1.0.

[16] Marvin Shingwe biness Neme Defoe and Edith Leoso. 2021. Knowledge shared at CIvIC-StRONg Listening Sessions, February, May 2021. Sessions supported by NSf Award No. 2044053..

[17] Annette D Drewes and Janet Silbernagel. 2012. Uncovering the spatial dynamics of wild rice lakes, harvesters and management across Great Lakes landscapes for shared regional conservation. *Ecological Modelling* 229 (2012), 97–107.

[18] Marisa Elena Duarte, Morgan Vigil-Hayes, Ellen Zegura, Elizabeth Belding, Ivone Masara, and Jennifer Case Nevarez. 2021. As a squash plant grows: social textures of sparse internet connectivity in rural and tribal communities. *ACM Transactions on Computer-Human Interaction (TOCHI)* 28, 3 (2021), 1–16.

[19] Gene W Eidson, Samuel T Esswein, Jill B Gemmill, Jason O Hallstrom, Tim R Howard, Josh K Lawrence, Christopher J Post, Calvin B Sawyer, K-C Wang, and David L White. 2010. The south carolina digital watershed: End-to-end support for real-time management of water resources. *International Journal of Distributed Sensor Networks* 6, 1 (2010), 970868.

[20] Great Lakes Indian Fish & Wildlife Commission. 2024. Mazina'igan: A Chronicle of the Lake Superior Ojibwe. http://data.glifwc.org/download/archive.maz/Summer2024.pdf. *Mazina'igan* (Summer 2024).

[21] Eric Greenlee, Blaine Rothrock, Hyeonwook Kim, Ellen Zegura, and Josiah Hester. 2024. "The Devil You Know": Barriers and Opportunities for Co-Designing Microclimate Sensors. *ACM J. Comput. Sustain. Soc.* (Aug. 2024). https://doi.org/10.1145/3685695 Just Accepted.

[22] Jordan Gurneau, Colleen O'Brien, Vivien Anne Rivera, Alexander Curtis, Maggie O'Connell, Amy Cottrell, Naomi Tillison, Jonathan Gilbert, John Coleman, Rajesh Sankaran, et al. 2022. In Situ Sensing of Manoomin (Wild Rice) Habitat to Create a Voice for Plant Relatives. In *AGU Fall Meeting Abstracts*, Vol. 2022. ED42A–02.

[23] George Hope Chidziwisano, Alex Mariakakis, Susan Wyche, Vitumbiko Mafeni, and Esau Gideon Banda. 2021. Nkhukuprobe: Using a sensor-based technology probe to support poultry farming activities in malawi. In *Proceedings of the 4th ACM SIGCAS Conference on Computing and Sustainable Societies.* 275–287.

[24] Heather R Hosterman, Kaylene Ritter, Nancy Schuldt, Darren Vogt, Deanna M Erickson, Olivia L Griot, Erin Johnston, Karena Schmidt, Evelyn Ravindran, Roger D LaBine, et al. 2023. Lake Superior Manoomin cultural and ecosystem characterization study. *Ecology and Society* 28, 3 (2023).

[25] Haider Mahmood Jawad, Rosdiadee Nordin, Sadik Kamel Gharghan, Aqeel Mahmood Jawad, and Mahamod Ismail. 2017. Energy-efficient wireless sensor networks for precision agriculture: A review. *Sensors* 17, 8 (2017), 1781.

[26] Albert Ernest Jenks. 1901. *The wild rice gatherers of the upper lakes: a study in American primitive economics.* Vol. 19. US Government Printing Office.

[27] Philo Juang, Hidekazu Oki, Yong Wang, Margaret Martonosi, Li Shiuan Peh, and Daniel Rubenstein. 2002. Energy-efficient computing for wildlife tracking: Design tradeoffs and early experiences with ZebraNet. In *Proceedings of the 10th international conference on Architectural support for programming languages and operating systems.* 96–107.

[28] Tahu Kukutai, Stephanie Russo Carroll, and Margaret Walter. 2020. Indigenous data sovereignty. (2020).

[29] Jacqueline Lavallee. 2022. *Asemaa Nitam (Tobacco First): Indigenous Healing Practices within the Ojibwe Tradition.* Ph. D. Dissertation. University of Toronto (Canada).

[30] Joycelyn Longdon, Michelle Westerlaken, Alan F Blackwell, Jennifer Gabrys, Benjamin Ossom, Adham Ashton-Butt, and Emmanuel Acheampong. 2024. Justice-oriented Design Listening: Participatory Ecoacoustics with a Ghanaian Forest Community. In *Proceedings of the CHI Conference on Human Factors in Computing Systems.* 1–12.

[31] Aditi Maheshwari, Abhay Kumar Aggarwal, and Andreea Danielescu. 2022. Designing Tools and Interfaces for Ecological Restoration: An Investigation into the Opportunities and Constraints for Technological Interventions. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems.* 1–17.

[32] Alan Mainwaring, David Culler, Joseph Polastre, Robert Szewczyk, and John Anderson. 2002. Wireless sensor networks for habitat monitoring. In *Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications.* 88–97.

[33] Feng Mao, Kieran Khamis, Stefan Krause, Julian Clark, and David M Hannah. 2019. Low-cost environmental sensor networks: Recent advances and future directions. *Frontiers in Earth Science* 7 (2019), 221.

[34] Kimberly R Marion Suiseeya, Margaret G O'connell, Edith Leoso, Marvin Shingwe Biness Neme Defoe, Alexandra Anderson, Megan Bang, Pete Beckman, Anne-Marie Boyer, Jennifer Dunn, Jonathan Gilbert, et al. 2022. Waking from paralysis: revitalizing conceptions of climate knowledge and justice for more effective climate action. *The ANNALS of the American Academy of Political and Social Science* 700, 1 (2022), 166–182.

[35] Angela Mashford-Pringle, Ruofan Fu, and Sterling Stutz. 2023. Mamwi Gidaanjitoomin/Together We Build It: A Systematic Review of Traditional Indigenous Building Structures in North America and Their Potential Application in Contemporary Designs to Promote Environment and Well-Being. *International Journal of Environmental Research and Public Health* 20, 6 (2023), 4761.

[36] Laura Matson, G-H Crystal Ng, Michael Dockry, Madeline Nyblade, Hannah Jo King, Mark Bellcourt, Jeremy Bloomquist, Perry Bunting, Eric Chapman, Diana Dalbotten, et al. 2021. Transforming research and relationships through collaborative tribal-university partnerships on Manoomin (wild rice). *Environmental Science & Policy* 115 (2021), 108–115.

[37] Lillian McGilp, Claudia Castell-Miller, Matthew Haas, Reneth Millas, and Jennifer Kimball. 2023. Northern Wild Rice (Zizania palustris L.) breeding, genetics, and conservation. *Crop Science* 63, 4 (2023), 1904–1933.

[38] Carlos Guerrero Millan, Bettina Nissen, and Larissa Pschetz. 2024. Cosmovision of data: An indigenous approach to technologies for self-determination. In *CHI'24: Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. ACM, 1–22.

[39] Chris Muashekele, Heike Winschiers-Theophilus, Kasper Rodil, and Uariaike Mbinge. 2023. Infusing Futuring into Community-based Co-design: A Pathway to Innovative Technology Design with Indigenous Communities in Africa. In *Proceedings of the 4th African Human Computer Interaction Conference*. 151–161.

[40] Kari Noe and Nurit Kirshenbaum. 2024. Where Generalized Equitable Design Practice Meet Specific Indigenous Communities. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–8.

[41] Madeline Nyblade. 2023. *First We Must Consider Manoomin/Psiŋ: Impacts of Climate and Land Cover Change on Wild Rice*. Ph. D. Dissertation. University of Minnesota.

[42] Madeline Nyblade, Daniel J Larkin, Darren Vogt, Rob Croll, G-H Crystal Ng, Joe Graveen, Kristen Hansen, Hannah Panci, Brandon Byrne, Bazile Panek, et al. 2023. CLIMATE CHANGE CONTRIBUTES TO LOSS OF WILD RICE (MANOOMIN/PSIN), THREATENING INDIGENOUS LIFEWAYS. *First We Must Consider Manoomin/Psiŋ: Impacts of Climate and Land Cover Change on* (2023), 47.

[43] James W Oberly. 2014. GLIFWC: THE FOUNDING AND EARLY YEARS OF THE GREAT LAKES INDIAN FISH. *Indigenous perspectives of North America: A collection of studies* (2014), 32.

[44] National Oceanic and Office for Coastal Management Atmospheric Administration. 2018. Restoring and Monitoring Lake Superior Coastal Wetland Manoomin. https://coast.noaa.gov/digitalcoast/stories/manoomin.html.

[45] Erick Oduor, Peninah Waweru, Jonathan Lenchner, and Carman Neustaedter. 2018. Practices and technology needs of a network of farmers in Tharaka Nithi, Kenya. In *Proceedings of the 2018 CHI conference on human factors in computing systems*. 1–11.

[46] Brendan O'Flynn, Rafael Martínez-Català, Sean Harte, Cian O'Mathuna, John Cleary, Catherine Slater, Fiona Regan, Dermot Diamond, and Heather Murphy. 2007. SmartCoast: a wireless sensor network for water quality monitoring. In *32nd IEEE conference on local computer networks (LCN 2007)*. Ieee, 815–816.

[47] Hannah Panci, Melonee Montano, Aaron Shultz, Travis Bartnick, and Kim Stone. 2018. *Climate Change Vulnerability Assessment, Version 1*. Technical Report. Great Lakes Indian Fish and Wildlife Commission (GLIFWC). 30 pages.

[48] Kelsey R Prihoda, Alexander Frie, Amy Schrank, and Donald R Schreiner. 2022. Workshop Summary: Habitat Management in the St. Louis River Estuary. (2022).

[49] Mompoloki Pule, Abid Yahya, and Joseph Chuma. 2017. Wireless sensor networks: A survey on monitoring water quality. *Journal of applied research and technology* 15, 6 (2017), 562–570.

[50] Spoorthy Raman. 2024. Culture and conservation thrive as Great Lakes tribes bring back native wild rice — news.mongabay.com. https://news.mongabay.com/2024/03/culture-and-conservation-thrive-as-great-lakes-tribes-bring-back-native-wild-rice/.

[51] SR Jino Ramson and D Jackuline Moni. 2017. Applications of wireless sensor networks—A survey. In *2017 international conference on innovations in electrical, electronics, instrumentation and media technology (ICEEIMT)*. IEEE, 325–329.

[52] Sage. 2025. Home | Sage — sagecontinuum.org. https://sagecontinuum.org/.

[53] Daniel Schallmo, Christopher A Williams, and Klaus Lang. 2018. An integrated design thinking approach-literature review, basic principles and roadmap for design thinking. In *ISPIM innovation symposium*. The International Society for Professional Innovation Management (ISPIM), 1–18.

[54] Vishal Sharma, Neha Kumar, and Bonnie Nardi. 2023. Post-growth Human–Computer Interaction. *ACM Transactions on Computer-Human Interaction* 31, 1 (2023), 1–37.

[55] Julianna Smith. 2023. Rights of Nature and Tribal Sovereignty: Protecting Natural Communities, Wild Rice, and Salmon in the United States. *Maryland Journal of International Law* 38, 1 (2023), 11.

[56] M. Stults, S. Petersen, J. Bell, W. Baule, E. Nasser, E. Gibbons, and M. Fougerat. 2016. *Climate Change Vulnerability Assessment and Adaptation Plan: 1854 Ceded Territory Including the Bois Forte, Fond du Lac, and Grand Portage Reservations*. Technical Report. 1854 Ceded Territory, Duluth, MN. 146 pages.

[57] Anh-Ton Tran, Grace Guo, Jordan Taylor, Katsuki Andrew Chan, Elora Lee Raymond, and Carl DiSalvo. 2024. Situating Datasets: Making Public Eviction Data Actionable for Housing Justice. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–16.

[58] United States Geological Survey. 2025. USGS Current Water Data for the Nation — waterdata.usgs.gov. https://waterdata.usgs.gov/nwis/rt.

[59] Alexander Khawaja Waheed. 2021. *Manoomin (wild rice) and environmental change at a significant river system of the Lac du Flambeau Band of Lake Superior Chippewa*. Master's thesis. University of Minnesota.

[60] Maggie Walter, Tahu Kukutai, Stephanie Russo Carroll, and Desi Rodriguez-Lonebear. 2021. *Indigenous data sovereignty and policy*. Taylor & Francis.

[61] Kaitlin Stack Whitney. 2015. Manoomin: The taming of wild rice in the Great Lakes Region. *Arcadia* (2015).

[62] Taryn Wilson, Hafeni Mthoko, Yusra Adnan, and Sarina Till. 2024. The Devil is in the deployment: Lessons learned while deploying an AI and IoT-enabled hydroponics grow tent with rural subsistence farmers in South Africa. In *Proceedings of the 7th ACM SIGCAS/SIGCHI Conference on Computing and Sustainable Societies*. 318–329.

[63] Marisol Wong-Villacres, Carl DiSalvo, Neha Kumar, and Betsy DiSalvo. 2020. Culture in action: Unpacking capacities to inform assets-based design. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–14.

[64] Marisol Wong-Villacres, Aakash Gautam, Wendy Roldan, Lucy Pei, Jessa Dickinson, Azra Ismail, Betsy DiSalvo, Neha Kumar, Tammy Clegg, Sheena Erete, et al. 2020. From needs to strengths: Operationalizing an assets-based design of technology. In *Companion Publication of the 2020 Conference on Computer Supported Cooperative Work and Social Computing*. 527–535.