Remote Sensing in the Great Lakes Basin: A History of Collaboration and Accomplishment

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Abstract

This paper reviews the development and application of remote sensing and related technologies to the Great Lakes and their surrounding watersheds over the last seventy-five years. The ultimate goal for those engaged in applying the art and science of remote sensing to the Great Lakes is to provide information necessary to manage this important resource. Over time, through collaboration across borders, this goal is coming to be realized.

Over the first two of five substantive sections the paper documents the development of the technologies following WW-II and then the use remote sensing to respond to the pollution and water quality issues that began to demand attention in the late 1960s and early 1970s. This in turn set the stage for the third substantive section that describes operational applications to meet a growing list of information needs. These needs were and are associated with monitoring of the environment of the Great Lakes Basin (GLB) which came to be seen as a complex system of inter-related features.

The section on the modern era provides more detail on some of the more recent research and advancements and more thoroughly explains the methods used and accuracies achieved. This era is also marked by ever increasing cross-border and cross jurisdictional cooperation and collaboration. There has also been significant growth in the use of synthetic aperture radar (SAR), LiDAR, and Unoccupied Aerial Vehicles (UAV's or drones) to complement and add to the previously dominant optical sensors.

The final section looks to what the authors see as the future for remote sensing in the context of the GLB. Fully supported, ongoing, binational, remote sensing programs will be needed to monitor the GLB continuously as development and fresh water demands increase. This will be especially so in light of climate change.

Keywords

Great Lakes, Remote Sensing, Radarsat, Landsat, aerial photography, photogrammetry

1. Introduction

This contribution to the Special Issue of the Canadian Water Resources Journal reviews the development and application of remote sensing and related technologies to the Great Lakes and their surrounding watersheds. The ultimate goal for those engaged in applying the art and science of remote sensing to the Great Lakes is to provide information necessary to manage this important resource. The importance and visibility of the Great Lakes was underlined in the cover article in the December 2020 issue of the widely read *National Geographic.* It refers to the Great Lakes as a resource "our planet needs to survive" and which "may be the continent's most valuable resource." The *National Geographic's* millions of readers and beyond have been presented with the challenges faced by the Great Lakes with the factors of climate change, pollution, and invasive species.

Another challenge we face in preparing this paper is that many of those who use the technologies of remote sensing for operational programs do not publish and document their work in the peer-reviewed literature. This issue was noted as early as 1981. (Ryerson, 1981) To meet this shortcoming June Thormasgaard led an effort by the USGS for the Department of the Interior to provide short one-page reports on the operational use of remote sensing. https://eros.usgs.gov/doi-remote-sensing-activities/. One of those reports by one of the current authors documented how muskrat populations could be estimated from space. https://eros.usgs.gov/doi-remote-sensing-activities/2015/fws/counting-muskrats-space

A quote from 1974 puts the challenge we face in monitoring these factors into perspective: "The intricate relationships between science and management are acutely evident when they involve the use of major earth resources. This intricacy is exacerbated when the science and management are divided between two nations and concern a shared resource as indivisible as a lake." (Ludwigson,1974)

A further quote provides another challenge: "The Great Lakes are too large to see, hence we are all blind." (Janssen et al, 2005) By detailing the developments leading to today's capabilities in remote sensing, we will show that our sight is improving.

This paper provides a window on the development of remote sensing technology and its application to the Great Lakes, both of which have benefited from international collaboration. This paper is an historical synthesis and sampling of the work undertaken in remote sensing related to the Great Lakes over the past several decades, including the development of some of the tools now being applied. It is intended to highlight the work that has been done: it is not meant to be a comprehensive review of all remote sensing work done on or around the Great Lakes – that would require much more than a single paper. It should be noted that because of the authors' experience, the emphasis tends to be on vegetation and the interaction of humans on the vegetated environment.

One of the interesting and challenging aspects of preparing this paper is that very little of the early work found its way into peer-reviewed journals. Much of the work is described in various reports of governments, agencies of governments, university research teams or in conference proceedings – some of which were peer reviewed, while many were not. Today the problem is almost the opposite. There has been an explosion of peer-reviewed publications related or applicable to monitoring of the Great Lakes Basin (GLB). Dedicated remote sensing sessions have been held at the International Association of Great Lakes Research annual conference for over 10 years. While this review looks back and provides an historical context for the present, it also looks to the future while highlighting the effective cooperation in applications and research that has grown between the two countries that share and manage this important resource.

This review is in six sections. The second section provides some historical context and begins at the end of the second World War. The early work, spawned in part by returning veterans with experience in the use of imagery during the war, led to the first use in the 1950s of the term "remote sensing." The context provides some details on the foundational tools that have impacted the application of remote sensing and discusses the role of the universities and governments in applications development. While the second World War was over, the cold war led to further military interest in and use of remote sensing technologies. Over time many of the cold-war developments found their way into civilian use and these have played a major role in monitoring associated with the GLB.

The third section deals with using remote sensing to respond to the pollution and water quality issues that began to demand attention in the late 1960s and early 1970s. It links some of the research and earlier activities that allowed us to look at the basin in a more complete and, simultaneously, a more localized manner than was previously the case. At the same time the early work called attention to some shortcomings in the methodologies used which in turn has led to significant improvements and the capabilities showcased in the remaining sections.

The fourth section shows the beginning of the maturation of a range of applications that can be characterized as environmental in nature. These respond to the growing view of the importance of the environment and how the environment is seen as a complex system of inter-related features. These views require remote sensing to have the ability to respond to issues affecting the GLB as a complex and ever-changing natural system. These issues include water and wetland management, climate change, and species at risk along with a more complete understanding of the Great Lakes as a system. There has also been a significant growth in the range, number, and type of imaging systems available, as well as in the techniques used to extract information from the outputs of these imaging systems. These developments have together made the work for those using remote sensing both more complex and more useful.

The first four sections summarize work that is largely accepted as operational, and the technologies noted are widely used. The fifth section on the modern era provides more detail on some of the more recent advancements to more thoroughly explain the methods used and accuracies achieved. Paradoxically, recent work has seen both more basin-wide studies and more studies of local issues such as algal blooms and invasive species. This modern era is also marked by ever increasing cross-border and cross jurisdictional cooperation and collaboration. There has been cross-border participation of both state and provincial agencies, national agencies, and academe. In this modern era there has also been significant growth in the use of synthetic aperture radar (SAR), LiDAR, and Unoccupied Aerial Vehicles (UAV’s or drones) to complement and add to the previously dominant optical sensors. The final section looks to what the authors see as the future for remote sensing in the context of the GLB. Fully supported, ongoing, binational, remote sensing programs will be needed to monitor the GLB continuously as development and fresh water demands increase. This will be especially so in light of climate change.

2. Historical Context

2.1. Introduction to the Context

By the end of the second World War, it was well accepted, at least in some circles, that aerial photography was a useful tool, whether for military or civilian use. With the end of the war many photo-interpreters were returning to civilian life in both Canada and the US, including those who would come to dominate the field – such as Robert N. Colwell in forestry.[i] The relationship between military use of imaging technology and civilian use which continues to this day was aptly described by Dr. Dieter Steiner, a pioneer at the University of Waterloo, when he said in a graduate course in 1970 that “one man’s tank trafficability map is another man's forest inventory.” (Personal Communication, R.A. Ryerson, January 15, 2022)

By the 1950s there was an upsurge in academic work, especially in geography, forestry, geology, agriculture and engineering. (Roscoe et al in Colwell, 1960, pp736; Hilborn, 1967). It was also in 1958 that the term "remote sensing" was introduced by Evelyn Pruitt of the U.S. Office of Naval Research. Remote sensing is defined as the science and art of identifying, observing and measuring an object without coming into direct contact with it.[ii] However, even as late as 1960 when the *Manual of Photographic Interpretation* (Colwell, 1960) and the *Elements of Photographic Interpretation Common to Several Sensors* (Olson, 1960) were published, there were those who argued that the science and art associated with the use of aerial photography was in its infancy, and it was "still too young" to publish a Manual on the subject. (Colwell 1960, vii) This tension between advocates for the use of remote sensing and those who think it premature continues today more than 60 years since it was first mentioned with reference to aerial photography. It is hoped that this paper will help reduce this tension.

In addition to those with training in interpretation, other returnees were experts in aerial survey. This led to the creation of a number of companies over the next dozen years such as Capital Air Surveys in Canada. In the U.S. in the Great Lakes Region, Mark Hurd Aerial Surveys of Minnesota (https://www.asprs.org/wp-content/uploads/pers/1984journal/sep/1984_sep_1291-1292.pdf) and Abrams Aerial Survey Corporation of Michigan (https://www.the-abrams-foundation.org/history/) were the dominant aerial photo mapping companies.

In general, the air photo mapping programs in the U.S. before and after WW II were initially driven by the military over the Great Lakes harbors and navigation channels for the U.S. Army Corps of Engineers. For example, they sponsored a 1977 development of a data base of land use and soil information for much of the Lake Erie watershed derived from aerial photography, soil maps and other data for a waste-water study. (Haack, 1977) The Corps of Engineers is still very much involved in remote sensing applications development in the Great Lakes region, particularly with topographic and bathymetric mapping. (See, for example, Reif et al, 2021.) Just before World War II WW-II), the U.S. Department of Agriculture (USDA) embarked on the earliest statewide coverages. Aerial photography was first used in the 1930's to assist with the new programs set up under the Agricultural Adjustment Act of the Depression Era New Deal.

After WW-II the USGS ramped up their topographic mapping with spring leaf-off aerial photography coverage over the region. Some of this early post WW-II aerial photography came to be used to study wetlands. (Wilcox et al, 2008) By the 1970's, USDA's crop compliance monitoring started using small format (35mm) aerial slide photography on an annual basis over agriculture areas. With the advent of digital aerial mapping cameras, the National Agriculture Imagery Program (NAIP) starting in 2003was created in Minnesota to replace the film-based systems nationwide with summer leaf-on 1-meter, non-stereo, 3-band colour aerial digital imagery even though the new digital mapping cameras were 4-band systems. A few states, including Michigan and Minnesota, paid for better stereo and colour infrared imagery. Because of the cost, the new NAIP crop compliance program was not flown annually in most states but came to be repeated approximately every two or three years.

Kodak Aerial Systems was the binding force for these aerial photo mapping programs and aerial survey companies since the mapping cameras all relied on large format (9" x 9") aerial film; all made in Rochester, NY- using Lake Ontario water in the manufacturing process.

2.2.The Foundational Tools

Introduction

Beginning in the 1960s and into the early 1970s, a number of what can be regarded as foundational tools were developed that would impact and further the use of remote sensing. These included Geographic Information Systems (GIS), high altitude airborne imagery, declassification of thermal data and Side Looking Radar (SLAR), publicly satellite imagery (beginning with ERTS/Landsat in 1972), and digital image analysis tools. But for SLAR, all of these were applied in the GLB soon after their development or declassification, as is outlined in the following two sections. It was not until the introduction of satellite SAR imagery and increasingly higher spatial resolution optical imagery in the early-mid 1990s (see sections 4 and 5) that the remote sensing toolbox was to change in any substantial way.

Although not an imaging system, the Global Positioning System (GPS), which started development in the late 1970s with a full constellation launched by 1993, became an integral component of all remote sensing systems today by providing accurate positioning of sensors and platforms. GPS led to a streamlining of the mapping process, with other global navigation satellite systems (GNSS) become available from other countries in the decades since.

Geographic Information Systems (GIS)

The most important foundational tool supporting the application of remote sensing was GIS invented in the mid-1960s. Roger Tomlinson "acclaimed as the Father of GIS, invented Geographic Information Systems as a way to analyze geographic data." (Science.ca) The development of the Canada Land Inventory GIS from the mid-1960s provided the first comprehensive look at Canada's side of the basin. That information is available through the Government of Canada. (See https://open.canada.ca/data/en/dataset/0c113e2c-e20e-4b64-be6f-496b1be834ee) These activities paved the way for the update in 1974-75 for the GLB as is more fully described in Section 3.

Early Airborne Sensing

A second foundational tool was the further development of airborne sensing – high-altitude photography (both colour and colour infrared) and thermal sensing. In the early 1970s the Canada Centre for Remote Sensing (CCRS) developed its airborne program with two objectives. The first was to showcase the value of airborne remote sensing while the second was to prepare users for satellite imagery, which was seen as similar to the small-scale high altitude airborne photography. CCRS acquired normal colour and colour-infrared aerial photography at a scale of 1:120,000 as well as thermal infrared data. Access to the latter was still restricted in certain respects as reported in the early development work by Slaney et al, (1967) "a frustrating aspect of this paper is that examples of the imagery cannot be published because of military security regulations." [iii] Similar data were being acquired in the US, but for some reason it was possible for Colwell to publish thermal imagery in the same 1967 publication where Slaney made his limiting comment. (Colwell, 1967)

By 1971 much of Southern Ontario was covered by the high-altitude imagery for work by B. Sen Mather of the Ontario Ministry of Transportation. (See Figure 1.) That imagery was later used in the basin-wide study initiated by the International Joint Commission (IJC) (see Section 3) as well as in other studies. A number of other data sets were collected by CCRS for a variety of applications directly related to the Great Lakes. Several of these were assessed for a cost-benefit analysis on the use of remote sensing compared to other methods, as is discussed in the next section. (Ryerson, 1981)

Satellite Imagery

While the US military had access to satellite imagery since August 18, 1960 (https://www.nro.gov/History-and-Studies/Center-for-the-Study-of-National-Reconnaissance/The-CORONA-Program/Fact-Sheet/), the arrival in 1972 of the third foundational tool, satellite data from ERTS-1, opened a new synoptic view and changed how we looked at the world. (Goward et al, 2017) The low resolution with pixel sizes of 60 x 80 metres presented a challenge for those used to working with low level aerial photography. However, over time the quality of the analogue photographic products improved, and tools were developed to better understand and use the digital information contained in each image. With the arrival of more advanced satellites with higher resolution and more spectral bands, the breadth and depth of available satellite-based information increased dramatically, leading to more applications as can be seen in Sections 4 and 5.

Commercial Optical High Resolution Satellite Imagery

In 2003, the Commercial Remote Sensing Space Policy (CRSSP) (https://www.space.commerce.gov/policy/u-s-commercial-remote-sensing-space-policy/) was created by President George Bush to promote the use of commercial, high resolution satellite imagery:

> “The fundamental goal of this policy is to advance and protect U.S. national security and foreign policy interests by maintaining the nation’s leadership in remote sensing space activities, and by sustaining and enhancing the U.S. remote sensing industry. Doing so will also foster economic growth, contribute to environmental stewardship, and enable scientific and technological excellence.”

Essentially, the National Geospatial-intelligence Agency (NGA, formerly the National Imagery and Mapping Agency (NIMA) was given the lead to contract with commercial vendors at the time on behalf of all defense and civilian agencies to acquire and access this high resolution satellite imagery across the planet.

In time, this new policy evolved into the NextView program (https://cad4nasa.gsfc.nasa.gov/images/NextViewLicenseGuide.png) which permitted access, processing and sharing of MAXAR imagery with international, federal, state, local governments and non-profit partners. This was a game changer for providing global access to multi-temporal, submeter satellite imagery across the GLB. Instead of relying on 30-meter Landsat for broad area ‘strategic’ planning, this high-resolution imagery allowed for ‘tactical’ planning and actions by land managers.

The next major policy announcement came in January 2008 when “Barb Ryan, the Associate Director for Geography at the U.S. Geological Survey, and Michael Freilich, National Aeronautics and Space Administration’s (NASA) Director of the Earth Science Division, signed off on a Landsat Data Distribution Policy that made Landsat images free to the public, instead of $600 per scene. The USGS announced the free-and-open data policy on April 21, 2008.”

https://www.usgs.gov/news/free-open-landsat-data-unleashed-power-remote-sensing-decade-ago When there was a cost for Landsat data an average of 53 scenes had been acquired daily from the archive. The number jumped to 5,775 per day when the data were free.

Digital Image Analysis

The projected arrival of digital data from satellites brought an increased attention to the development of the fourth foundational tool, digital image analysis. Some of this work relevant to the Great Lakes began in the mid-late 1960s by Steiner before he joined the faculty at Waterloo. (Steiner and Haefner, 1965; Steiner and Maurer, 1967) The initial development of the tools to interpret digital data was the topic of research being done in the late 1960s through the early-mid 1970s by both government agencies (Shlien and Goodenough, 1974; Goodenough and Shlien, 1974) and academe (Todd et al, 1973; Steiner et al, 1972). As with other aspects of remote sensing, work on digital image analysis was first begun in the military and the first image analysis systems were procured by the military. The first system sold to a civilian agency was General Electric's Image-100 delivered to CCRS in March 1974. (USGS EROS Data Center also obtained an Image-100 shortly thereafter.) The first paper published on that system's application showed test results over several tests sites, including the region around Thunder Bay. (Economy et al, 1974) By the early 1990s, the Image 100 was on display at Canada's National Science Museum.

2.3. The Early Role of Government in the Development or Remote Sensing Technology and Applications

The United States

The early development of both the technologies and applications of remote sensing, including the definition and first use of the term "remote sensing," owed a great deal to government programs, especially the US military. This link to the military is clearly indicated by the sources of funding for many of the early studies and technology developments. (See for example Slaney, 1967; Goodman, 1954; and much of the work cited in Colwell, 1960.) NASA also played a prominent role. (Hardy, 1973; Kiefer et al, 1973; Scarpace et al, 1979; Chipman et al, 2004; etc.) Over time government agencies charged with the management of natural resources came to be more active. For example, sixteen wetlands were identified for study with aerial photography in 1960 by the USGS and these wetlands have now been monitored for over 50 years. (Wilcox et al, 2008) In other cases it was the state or state agencies that supported studies, often with federal agencies involved. (Kiefer et al, 1973; Haack, 1977; Scarpace et al, 1979; etc.) Support continued from NASA, NOAA (Lathrop and Lillesand, 2002), EPA (Hatch and Bernthal, 2008), the USGS (Reese et al, 2002), and the active involvement of the research arm of the Army Corps of Engineers (Rief, 2021)

With the forestry sector, after WWII, many of the aerial photo interpreters were put to work mapping forests across the GLB for the provincial, state and federal forest agencies. At the western end of the Lake Superior Basin, townships across the USDA Superior National Forest were mapped in 1948 by species, size and density through an intensive photointerpretation campaign combined with field forest surveys down to 5 acres.

State forest management programs like the Minnesota Department of Natural Resources, Resource Assessment relied on summer black and white infrared 1:15,840 scale, large format, aerial photos as their 'standard' for identifying conifer stands by species through the 1980's.

Aerial photography would be contracted by county about every seven to ten years across northern Minnesota. The same type of imagery was used in Ontario for forestry and agricultural studies through the 1970s.

The 1980's witnessed a shift in demand in the US for hardwood species such as aspen (*Populus tremuloides)* in the GLB. That change required a shift in film types as well as a specific seasonal acquisition. Minnesota followed the Ontario Department of Lands and Forest lead in using autumn, colour infrared aerial photography as the new standard for identifying most hardwood and conifer forest stands by species. In 1978, the Michigan Department of Natural Resources (MDNR) developed the Michigan Resource Inventory System (MIRIS) which used aerial photography to identify land use and land cover types with a 2.5 acre minimum polygon size (Pijanowski and Robinson, 2011).

With the potential pollution caused by run-off from some 3,430 landfills across the state, the Illinois Geological Survey developed an early interest in monitoring landfills using a variety of remote sensing technologies. (Stohr et al, 1987) That activity continues. (Stohr and Filippini, 2018)
Less well-known in today's remote sensing community is the significant contribution made by small format aerial camera systems for forest management and agriculture monitoring. Victor Zsilinszky (1968) with the Ontario Department of Lands and Forest, Timber Branch (and later the head of the Ontario Centre for Remote Sensing) published the "Supplementary Aerial Photography with Miniature Cameras" paper which led the way for using small format (35mm), aerial photography systems. Steiner at Waterloo had 70mm cameras with films sensitive to the bands on ERTS data, as did CCRS. Merle Meyer at the College of Forestry, University of Minnesota, adopted Zsilinszky's approach. Meyer used and promoted small format imagery for many decades because the approach was more affordable for repeat coverage compared to large format systems. Meyer et al. (1982) is an example of the many reports published over the years demonstrating this. Pitt et al. (2001) is an example of small format aerial photography's application in Ontario into the 2000s.

Another relatively unknown use of small format film camera systems was the Aerial Compliance Program (ACP) of the U.S. Department of Agriculture. (USDA 1985). Started in 1972, ACP imagery was acquired every summer over U.S. agriculture areas across the GLB for USDA offices to verify if farmers complied with various farm programs.

Another early approach that is still used was documented by Fleming and Dixon (1981) when they published the "Basic Guide to Small-format Hand-held Oblique Aerial Photography." One of the spinoffs from this work for the Great Lakes was that oblique shoreline imagery was acquired on the U.S. side by state coastal programs beginning in the 1970's. An example for Wisconsin can be seen at https://www.sco.wisc.edu/2021/10/15/the-wisconsin-shoreline-inventory-and-oblique-photo-viewer-an-effort-born-from-collaboration/).

Located at the western watershed for Lake Superior, in 1997 the University of Minnesota, Cloquet Forestry Center hosted The First North American Symposium on Small Format Aerial Photography. (Bauer et all. 1997) What was supposed to be a small meeting between Canadian and U.S. practitioners around the Great Lakes, ended up being a week-long symposium including aircraft demonstrations and a small delegation from the UK among the nearly 100 participants. While this was the first and last symposium for this technology due to the emergence of digital camera systems, it shows the sort of attention that was being paid by cross-border groups to the many systems that were emerging to monitor the GLB.

Much of the work in the universities in the United States cited in Section 2.4 was supported by funding and/or subsidized data by NASA, USGS, Environmental Protection Agency (EPA), and other agencies.

Canada

In Canada much the same picture emerged as in the United States, albeit with the major support coming from civilian agencies, not the military. By 1971 CCRS was the central agency providing advanced airborne data for research projects and it added ERTS-1 data in 1972. Several other government organizations, both federal and provincial, were involved in developing applications including many closely related to the Great Lakes.

One of the federal organizations involved in remote sensing and the GLB was the Canada Centre for Inland Waters (CCIW) which provided guest lecturers to some of the early university programs and had one of their well-known scientists, Keith Thomson, hired by CCRS. Robert Bukata joined the CCIW in 1972. He and his colleagues carried out work on remote sensing for water quality studies of the Great Lakes over several decades. (Bukata et al, 1977; Bukata et al 1979; Jerome et al, 1982; Bukata et al, 1983 and Bukata, 2005.)

Other federal organizations in Canada active in remote sensing with interest in the GLB included the Forest Management Institute (FMI) which started with aerial photography (Aldred, 1967; Murtha, 1972), pollution damage (notably in the Wawa area of Ontario) on airborne and satellite data (Murtha 1972a and 1973) and later FMI became the first client for the image analysis system sold by one of the early leaders in the field – Dipix Systems. Agriculture Canada expressed an early interest in crop area estimation, albeit most of that work was in western Canada.

Further work on vegetation damage was done in Agriculture Canada on the detection of bacterial blight of field beans using colour infrared aerial photography. (Philpotts and Wallen,1969; Wallen and Philpotts, 1971) That work led to the eventual eradication of the disease that threatened a high value crop typically grown annually on 55,000 to 80,000 acres in Ontario. Work on crop area estimation of white beans and soybeans in southwestern Ontario began at CCRS in the mid-1970s and grew out of the work by Wallen and Philpotts. (Ryerson et al, 1977; Ryerson and Wallen, 1977; Ryerson et al, 1979)

In 1973, CCRS staffed an Applications Division that encouraged the development of applications and methodologies to better use remote sensing. It was the CCRS Applications Division that played a key role in the first comprehensive monitoring of the GLB as described in Section 3. Other early activities of CCRS related to the Great Lakes included work by Alfoldi on Lake St. Clair that showed that dredging the channel would have less impact than continuing to allow ships to do their own dredging with the action of their propellers. (Alfoldi, 1974, cited in Ryerson, 1981) Another CCRS study related to the GLB used thermal sensing to identify areas in the Niagara Peninsula where sensitive high quality wine grapes could be grown. That work resulted in a map of potential vineyard sites by Dr. John Wiebe that led to a dramatic increase in the size of the Niagara wine growing region as well as improving vineyard management practices to reduce the potential for frost damage. (Ryerson, 1974) That map was improved and updated by Fisher and Slingerland. (2016)

As CCRS was getting its start, the Ontario government was entertaining a proposal to start an Ontario Centre for Remote Sensing (OCRS). (Collins et al, 1972) The OCRS was established under the leadership of Victor Zsilinszky in September 1973 (Sayn-Wittgenstein et al, 1999) and it carried out a number of mapping programs in the GLB for several agencies of the Government of Ontario. The OCRS studies focused on topics as varied as wetlands, forests, and land cover. A Conservation Authority worked with OCRS to apply airborne thermal remote sensing to detect ground water discharge. (Ryerson, 1981) The Great Lakes Survey Unit of the Ontario Ministry of the Environment assessed CCRS airborne thermal data for thermal plume analysis over several years near the nuclear plants at several locations on the Great Lakes. It was found that the thermal data reduced the costs of assessing the plumes under a wide variety of situations. (Ross and Kinkead, 1976) Another group in the Ministry of Environment assessed airborne remote sensing to assess aquatic plant growth in the Kawartha Lakes in 1972-73. This was an early indication of the usefulness of simple colour aerial photography for estimating the general extent and density of aquatic plant growth. However, it was also shown that for more detailed studies it was more effective to simply increase the amount of field work. (Wile, 1973) Interestingly, these findings are consistent with those of White et al (2020) almost fifty years later. White et al suggested that low level drone imagery would be better for more detailed studies when compared to more conventional aerial photography.

2.4.The Early Role of the Universities in Applications Development

This subsection introduces some of early work on remote sensing in the GLB that came in the late 1960s and early 1970s with the rapid growth in research and the education of remote sensing specialists at several universities on both sides of the border. This growth in activity led to many localized studies that laid the groundwork for the work that was to come. While most work in this early era was state or province focused, at the same time there was the beginning of some national-level activities that led to the broader view that was necessary to deal with a watershed that covers 240,000 km^2 over two countries and nine states and provinces.

There were several hotbeds of remote sensing in the universities on both sides of the border. These usually operated with government support – either federal or state/provincial. Those discussed here are the ones that were published in major journals at the time or that became highly visible.[iv] There were early cross-border linkages between academic programs and people.

Some of the earliest work was undertaken at Northwestern University with a PhD dissertation by Marjorie Smith Goodman (Goodman, 1954) with the substantive results published several years later. (Goodman, 1959) In her work funded by the US Office of Naval Research she developed methods to identify farm crops of the types grown in the GLB. Her work was extended by Ryerson at McMaster (1971) and Waterloo (1975). Ryerson used crop type mixes and farm building design to identify farm types and provide an estimate of livestock types and numbers and their location. That work was subsequently applied across Ontario by the Pollution from Land Activities Reference Group in the Canadian side of the GLB. (See Section 3.) Barry Wellar, a Professor of Geography at the University of Ottawa, also did his PhD at Northwestern involving image interpretation of urban areas. (Wellar, 1969) The work by Wellar was in part the basis for some of the urban mapping activity described in Section 3.

In the 1970s the largest single US university group involved in remote sensing associated with the GLB was at the University of Wisconsin.[v] The Wisconsin remote sensing community was first organized as the "Environmental Monitoring and Data Acquisition Group," which then established a research center and in the Environmental Remote Sensing Center (ERSC) an MS/PhD program under the auspices of the Institute for Environmental Studies (now the Nelson Institute). The Wisconsin group did some early work evaluating Landsat-1 (ERTS-1) for statewide inventory (Clapp et al, 1973), assessment of land resources (Kiefer et al 1973), regional land use planning (Clapp et al 1974), and lake trophic status. (Scarpace et al 1979). The work at Wisconsin led to what became the most popular undergraduate textbook in the field (Lillesand and Kiefer, 1979). Water quality work was continued in the 1980s (Lathrop and Lillesand, 1986; Lathrop et al, 1986) and a PhD was done on lake ice by Wynne. (Wynne et al, 1996) Through the 1980s and into the 1990s work was also done on remote sensing of forest properties. (Bolstad and Lillesand, 1992; Fassnacht et al 1997; and Chipman at al 2000)

A group including a team at Cornell (Anderson, 1971; Anderson et al, 1972) developed a land use classification system specifically for use with satellite and high-altitude airborne data. Such a classification scheme was seen as necessary since the existing classification schemes such as that proposed by Clawson (1965) were not amenable for use with lower resolution satellite data. The land use classification work was among several remote sensing studies done at Cornell by Hardy, Philipson and others that contributed either directly or indirectly to remote sensing monitoring programs in the GLB. (Hardy,1973)

Work was being undertaken at Purdue by Baumgardner, Todd and others using digital image classification approaches applied to both airborne and satellite data. (Todd et al, 1973; Todd and Baumgartner, 1973) The Purdue work is further discussed in Section 3 below.

The key player in Minnesota was Dr. Merle Meyer, another decorated returning veteran who received his Masters and PhD degrees after WW-II. In 1972, he was appointed the first director of the Remote Sensing Laboratory in the College of Forestry's (now Natural Resources). During his time at the University of Minnesota, he taught a variety of courses on photo-interpretation and remote sensing at the undergraduate and graduate level while conducting research on crop and tree detection, wetland classification and related topics. Meyer was also part of the team that in 1973 led one of the first NASA sponsored evaluation projects of the new ERTS-1 imagery: "ERTS-1 Applications to Minnesota Land Use Mapping" In this early project both cultural and vegetative landscape features were mapped from autumn ERTS imagery. https://conservancy.umn.edu/bitstream/handle/11299/205800/L1040.pdf?sequence=1 Lillesand was on faculty in Minnesota for several years until 1983.

NASA funded the University of Minnesota, Remote Sensing Laboratory in the early 1990's to develop FORNET:https://www.hq.nasa.gov/hpcc/reports/annrpt97/accomps/iita/WW169.html FORNET was designed to deliver scanned aerial photography, Landsat imagery and forest inventory stand polygons to the Minnesota Department of Natural Resources (MNDNR) field foresters using telephone modem communications. This required developing Mapserver released in 1994 (https://en.wikipedia.org/wiki/MapServer) by Steve Lime, MNDNR as an open-source software designed for delivering imagery and maps over ridiculously slow modems (33k by today's standards) to district foresters' PC computers. This was the dawn of the internet, many years before commercial companies such as ESRI thought of delivering imagery and maps over the internet. This is a classic example of how remote sensing data from both satellites and aircraft could be digitally delivered over the internet to foresters. The Mapserver open-source software continues to be developed (https://mapserver.org/sq/about.html) and used by the Minnesota Department of Natural Resources. Tom Kralidis with Environment and Climate Change Canada is also another Mapserver developer for the Great Lakes.

A seminal paper described the elements of photo-interpretation was published by Dr. Charles Olson, Jr., then at the University of Illinois, Urbana and later at the University of Michigan, Ann Arbor. (Olson, 1960) The elements listed were shape, size, tone, shadow, pattern, texture, site, association, and resolution. These elements are still being used and cited today in work that is aimed at interpreting imagery with computers in a way that mirrors how a human interprets imagery. This is discussed more fully in Section 3.

In Canada much of the academic work on remote sensing done in the late 1960s and early 1970s was carried out at universities in the GLB. The availability of funding and government support in the form of subsidized airborne imagery from CCRS began in earnest in the early 1970s. By 1973 CCRS had established an Applications Division and by 1974 CCRS was providing academics and others free access to the Image 100 Image analysis system. (Economy et al, 1974)

In Canada the largest university group involved in remote sensing was at the University of Waterloo where several faculty members worked in the field. Steiner's focus was on digital image analysis and computer mapping (Steimer et al, 1972) while Erb worked on air photo interpretation (Erb, 1967) and Kesik applied remote sensing to geomorphology. After Steiner left LeDrew joined the faculty and Howarth moved to Waterloo from McMaster. Work at Waterloo then focused on environmental issues, including some of the earliest work in Canada on climate change and remote sensing. (Cihlar et al, 1988; Ledrew at al,1995) Donald Clough, a professor of management studies at Waterloo, was important as the key consultant engaged to set up CCRS.

At McMaster, Wood was doing work on crop recognition and farm practices using aerial photography (Wood, 1967; Ryerson and Wood, 1971), and tropical agriculture development. (Wood, 1972). Howarth, a recent PhD graduate from the UK joined the faculty in 1968 and focused on geomorphology and photogrammetry. Others had a peripheral interest in aerial photography and topics such as land use classification. (Reeds, 1972)

Protz at the University of Guelph worked on the remote sensing of soil and was known for his contributions to various national working groups and for some of his graduate students including Josef Cihlar and Brian Brisco. Collins was particularly interested in the technical aspects of aerial and ortho-photography, but perhaps his major contribution was, like Clough, as a builder. He directly contributed to the formation of the Ontario Centre for Remote Sensing and was an early advisor to CCRS. (Collins et al, 1972) Both the Ontario Centre and CCRS were to make major contributions to remote sensing of the GLB. At the University of Toronto Vlcek and

Munday were active, the latter with a great deal of work on water resources and coastal environments.

2.5. Early International Cooperation

Informal linkages between the US and Canada had already begun by the late 1960s. Steiner of the University of Waterloo was a guest lecturer at Purdue where he encouraged some of the early image analysis work. Colwell was a guest speaker at an early meeting on photo interpretation in Ottawa (Colwell, 1967), while Anderson was among a number of international speakers at a meeting on agricultural typology held at McMaster in 1972. (Anderson, 1972) Anderson and Hardy served on a PhD committee related to the GLB (Ryerson, 1975), while a number of Canadians did PhDs at several US universities including the first PhD in remote sensing earned by a Canadian (Peter Murtha at Cornell in 1968). Others who earned early PhD's in the US included Barry Wellar at Northwestern (Wellar, 1969), Ellsworth Ledrew at Colorado in 1976 (work on the Arctic), and, at Kansas, both Josef Cihlar (Cihlar, 1975) and Brian Brisco (Brisco, 1985).

3. Pollution and Water Quality Demand Attention

A 1969 set of studies on water quality in the lower Great Lakes requested by the IJC "demonstrated that diffuse land drainage sources of pollutants were not only significant but also difficult to measure." The result was that the Governments of Canada and the United States signed the Great Lakes Water Quality Agreement of April 15, 1972. That agreement "requested the International Joint Commission to investigate pollution of the boundary waters of the Great Lakes system from agricultural, forestry and other land use activities." It was concluded that a "much better definition of the impact of land use activities practices and programs on water quality in the Great Lakes" was needed. Following a series of meetings, a study plan was developed and submitted. (International Reference Group, 1974)

Several questions were posed in the aforementioned study plan. Those most germane to this paper asked if the boundary waters of the Great Lakes System were being polluted by drainage from agriculture, forestry, urban and industrial land development, recreational and park land development, utility and transportation systems, as well as natural sources. And if so, to what extent, by what causes, and where? Other concerns expressed related to land use, landfills, land dumping, and livestock feeding operations. It was concluded that basin-wide land use/land cover mapping was indicated as well as a study of livestock concentrations close to stream courses. This was the first bi-national remote sensing-based mapping program proposed for the GLB, and one of the largest bi-national mapping programs undertaken up to that point by anyone anywhere.

How best to do the land-cover/land-use mapping was discussed at several Canada-US meetings, including one in Rochester New York on July 12-13,1973. That meeting, focusing on remote sensing, was attended by Ryerson and Goodenough, scientists representing Canada and Hardy of Cornell and Baumgardner of Purdue represented remote sensing on the US side. Baumgardner proposed that the mapping of land cover could be done quickly and at low cost using the concept of spectral signatures applied to ERTS-1 digital data. The first cost estimate presented in January of 1973 for such mapping was $100,000 for both Canada and the US: that had grown to almost $500,000 at the time of the Rochester meeting where results of a test were presented. (Todd and

Baumgardner, 1973) Hardy of Cornell proposed an alternative approach based on his work using enlarged diazo colour composites of ERTS-1 data. (Hardy, 1973)

The Canadian side did an assessment of the two approaches proposed by their US colleagues and remained unconvinced as to the accuracy and costs of the proposed approaches using just satellite data. In the initial tests of the approach proposed by the Purdue team the problems were related to a combination of lack of ground verification data and the similarity of the appearance on the imagery of very different features. Such problems included confusion between orchards and forests, calling golf courses and parks agriculture and, more importantly, bare ground in rural areas was often identified as urban. The latter problem became very important in the implementation phase of the project when open pit mines in the Mesabi iron range in northern Minnesota were identified as urban areas. This in turn affected population projections and projected pollution loadings. Cloud cover also became an issue in the implementation. In the end other procedures were adopted to finalize the mapping in the US, leading to more useful information. (International Joint Commission, 1980)

After reviewing the Purdue and Cornell approaches, Canada decided to develop a hybrid approach as described below. (Thie et al, 1973) The hybrid approach used the Canada Geographic Information System (CGIS) as the base into which all information was overlaid on drainage basin maps. While the Canada Land Inventory information already in the CGIS was several years old, the information was judged to be as accurate for rural areas as a new mapping using satellite data would be. The information on crops was updated using the most recent Census information on crops grown. The minimum mapping unit for this census information used in the GLB study was the smallest standard geographic area for which census data are disseminated – usually an aggregate of several farms. All urban areas and those influenced by urban areas (such as the Golden Horseshoe running from Oshawa to Niagara Falls) were mapped using 1971 high altitude imagery from CCRS at a scale of 1:120,000 to 1:137,000. The unsettled and largely forested areas (i.e. non-urban and non-agricultural) of northern Ontario were mapped using visual interpretation of ERTS-1 photographic products overlaid on the CLI inventory maps.

A detailed outline of the Canadian approach, including a workflow and discussion of problems encountered and their solutions was presented to the IJC Land Drainage Reference Group in July of 1974. (Ryerson and Gierman, 1974) In March of 1975, a second and final report provided an explanation of the land use classifications developed, how data were collected/created, and the resulting tables produced for each watershed and county by the CGIS. The final report including all tables was 584 pages. (Gierman and Ryerson, 1975) That report is now with Environment and Climate Change Canada.

Looking back from the vantage point of today, our work with satellite imagery from the early 1970s seems simplistic at best. This is especially so when compared to the precision and accuracy with which basin-wide, bi-national information can be collected using today's satellite data as described by Bourgeau-Chavez (2015) and others in the following sections. While the early work was relatively unsophisticated, it did provide a beginning and some useful lessons were learned. The importance of ground verification data was underscored, as was the need for a clear understanding of the environment being sensed. Perhaps the most important finding was that while the assumption behind spectral signatures was fine in theory (i.e., different objects have different and unique spectral signatures), the reality was that spectral signatures only covered tone, just one of the nine elements of photointerpretation identified by Olson in 1960.

In 2008 Olson wrote on the need for improved accuracy of information derived from the analysis of remote sensing data, especially with reference to the use of "computer techniques." He called for the use of elements other than tone by those analyzing digital data. To increase accuracy methods had to be developed to replicate those other elements of interpretation used by the human interpreter: shape, size, shadow, pattern, texture, site, association, and resolution. (Olson, 2008) Early work on air photointerpretation referred to the development of photographic keys developed by expert interpreters that allowed less experienced interpreters to interpret imagery like an expert. (Philipson and Liang, 1982) As early as 1989, Ryerson suggested such keys were a form of expert system that would eventually lead to the use of artificial intelligence (AI). An early attempt to link concepts from photointerpretation to artificial intelligence and digital image analysis was described by Fung et al (1993) More recently, Portelli and Pope (2022) have suggested that more attention should be paid to human factors research. Today, as is described in the next sections, such methods and new thinking are being developed and applied to the GLB, leading to more accurate knowledge being derived from remotely sense data than was heretofore possible.

Not all of the work for the International Joint Commission used more sophisticated airborne remote sensing or satellite data. The simplest imagery widely available, panchromatic aerial photography at a scale of 1:15,840 (equivalent to four inches per mile), was also used in the pollution-driven studies. A major area of interest with regard to pollution was the location and impact of livestock concentrations near stream courses. While it was initially thought that Census data might be used to make these assessments, it was found that the livestock concentrations were assigned to the location of the farm headquarters – which was often not where the livestock were located. A team was organized by the Engineering Research Service and the Soil Research Institute of the Canada Department of Agriculture to locate livestock concentrations close to streams using the approach developed by Ryerson and Wood (1971) and further refined by Ryerson (1975). (International Reference Group, 1974, p 151.) The precision with which livestock concentrations could be located using simple aerial photography led to a far more precise modelling of the impact of livestock concentrations on water quality.

4. Environmental Applications Development Matures

Introduction

Over the last two decades the application of advanced remote sensing technologies in the GLB has moved from applications research and the occasional operational application to delivering information to meet operational resource management mandates. The creation of the Great Lakes Alliance for Remote Sensing (glars.org) in 2021 out of a binational collaboration including the CCRS, Environment and Climate Change Canada, Michigan Tech University, University of Minnesota and SharedGeo is an indication of the move from research to application. The Alliance came about in response to the Great Lakes Restoration Initiative (GLRI) project that started in 2016 to better address wetland mapping across the basin. New multi-temporal wetland mapping approaches and datasets are provided at the GLARS website. Increasingly, remote sensing is answering the needs users have for prescribed or required accuracies, as detailed in

White et al (2020). That the technology can often meet the operational needs of a resource manager is an indicator of remote sensing becoming mature, defined as being “fully developed or established.” (Barber, 1998)

At one time, those engaged in remote sensing seemed almost divorced from the real world of the resource manager. There were cases of remote sensing specialists developing different standards for estimating accuracy as identified by Olson (2008). In other cases, different approaches to land use classification were adopted (Anderson et al, 1972; Ryerson and Gierman 1975) since the remote sensing technologies available to them could not deliver the traditionally accepted accuracy standards for such mapping and even then, accuracies were often less than traditional methods provided.

The benefits of remote sensing were occasionally overstated, and the limitations often downplayed. Problems with the technologies were sometimes ignored, leading to mistrust among some of those in the user community. That has changed. Gallant (2015) met the issue head on when she identified the challenges of remote monitoring of wetlands. Today those in the Great Lakes remote sensing community are meeting the limitations head-on and with confidence, as indicated in White et al (2020). Before identifying the technologies that could best meet the very specific needs of and accuracies required by their user, they identify 16 issues that are constraints on the use of remote sensing, and but six obvious advantages of using remote sensing. The confidence shown by identifying the constraints in such detail is based on the knowledge that remote sensing can now deliver information that is required for resource management if it is used wisely and with appropriate attention to the limitations of the technology.

The new-found confidence in remote sensing is a result of a number of factors. First, and perhaps most important, has been the teamwork and cooperation that sees the engagement of users/resource managers in both setting research priorities and in identifying applications development opportunities. Second, the accomplishments to date have been based on sound science and rigorous field testing. Third, the results have been widely and generously shared across borders – state, provincial, and national. As a result of the first three factors more people are engaged in effectively using remote sensing than ever before.

While there are more people using remote sensing than ever before, there have been new sensors (Light detection and ranging (LiDAR) and radar), new sensor platforms such as drones, and new approaches to image analysis that use more of the elements of image interpretation laid out by Olson (1960; 2008). In the past, remote sensing specialists often had a bias to one technology or another because of the data they had access to and their source of funding - no matter the applicability of that technology. This leads to the hammer and nail syndrome: if the only tool you have is a hammer, every problem looks like a nail. With such a worldview, assessments of capabilities were often performed with a focus on the output of one sensor or analysis approach, not by the resource manager’s requirement. Today, the silos are breaking down and examples can be shown of groups using an amalgam of sensors and approaches (Bourgeau-Chavez, 2015), although there are many issues that complicate the use of multi-sensor and data processing approaches (Mahdavi et al, 2018). At the same time, closer attention is being paid to the resource manager's needs. (White et al, 2020) Lastly, there has been what Coops (2020) calls democratization of data. Today, a great deal of high-quality data is easily accessible, leading him to conclude that we are in “the golden age of sensing.” Scientists and resource managers in the

Great Lakes Basin are together participating in this golden age and doing so while at the same time contributing to and drawing from the wealth of knowledge available around the world.

The balance of this section outlines a sample of operational or demonstrated applications, mostly environmental in nature, that remote sensing can now address with some confidence.

Land Use and Land Cover Mapping

Land use and land cover mapping continued to be a focus of research and application development efforts across the GLB. Wetlands are such an important aspect of land cover that they are addressed in their own subsection.

Through the late 1990s to the early 2000s, Lillesand at Wisconsin led the development of a new protocol for statewide land cover mapping, which was undertaken by the Wisconsin Department of Natural Resources. The protocol was also adopted by Minnesota and Michigan, under the auspices of the Upper Midwest Gap Analysis Project (UMGAP), leading to uniform land cover data across the region. (Personal Communication: J. Chipman Nov 18, 2021; Lillesand et al, 1998; Reese et al, 2002) The improvements from early work are clear in the accuracies achieved. “The final data had overall accuracies of 94% for Anderson Level I upland classes, 77% for Level II/III upland classes, and 84% for Level II/III wetland classes. Classification accuracies for deciduous and coniferous forest were 95% and 93%, respectively, and forest species' overall accuracies ranged from 70% to 84%.” (Reese et al, 2002)

The success of the "UMGAP" land cover collaboration led to a follow-up effort, the Upper Great Lakes Regional Earth Sciences Applications Center (Upper Great Lakes RESAC), involving the same three states (Minnesota, Wisconsin, and Michigan). Several aspects of remote sensing were pursued, most notably monitoring water quality in inland lakes. The primary mover on that effort was a team at Minnesota (Marv Bauer, Pat Brezonik, Leif Olmanson, and others). Wisconsin's component of the Upper Great Lakes RESAC was the "Satellite Lake Observatory Initiative" (SLOI) and, among other things, produced a statewide assessment of water clarity (Secchi depth) in approximately 8000 lakes statewide. That activity was then taken over by the Wisconsin Department of Natural Resources and turned into an ongoing operational program. (Chipman et al, 2004) More recently there have been several landcover mapping projects usually based on Landsat such as the example posted on the North American Environmental Atlas using 2015 Landsat-derived landcover maps. http://www.cec.org/

One of the aspects of land cover that has been paid a great deal of attention is associated with forest management. Outside of the ERSC, remote sensing work in forest ecology was done by others at the University of Wisconsin including Volker Radeloff, David Mladenoff, and Phil Townsend. Marv Bauer at the University of Minnesota and his students did a number of similar projects and collaborated intermittently with Lillesand and others at ERSC. For the Great Lakes as a region, there was the late 1990’s Great Lakes Ecological Assessment led by Dr. Dave Cleland, USDA Forest Service (https://www.nrs.fs.fed.us/gla/index.htm) This was a massive, multi-agency, multi-layered effort to document all aspects of the Great Lakes forest ecosystem on the U.S. side where Landsat and AVHRR forest maps were featured.

In Canada there has been a great deal of work done on remote sensing for forestry, including forest inventory, assessing clear-cut regrowth, pest damage, and pollution damage. One of the five Forest Research Centres operated by the Canadian Forestry Service is the Great Lakes

Forestry Centre in Sault Ste Marie with a focus on forest pests, climate change and forest fire studies, and forest ecosystem studies. In 1997 a group of foresters was assembled to assess the use of remote sensing for forest vegetation management. They evaluated remote sensing to supplement field data collection for forest management. They concluded that "aerial photographs appear to offer the most suitable combination of characteristics." These characteristics included high spatial resolution, stereo coverage, a range of scales, versatility, and moderate cost." (Pitt et al, 1997)

Cross-border cooperation continued from the mid-1990s to 2010 with CCRS collaborating on the NASA-sponsored North American Landscape Characterization (NALC) program.[vi] The program, led by Ross Lunetta of the USEPA, involved first acquiring the best quality Landsat MSS coverage of the continent for what were called three 'epochs:' the late 1970s, mid 1980s and early 1990s (Lunetta et al., 1998a, 1998b). The program leads sought regional land cover/land use experts to generate a consistent product for the continent. CCRS was invited to contribute the Canadian Landsat MSS coverage and classifications. At the time MSS distribution was in the private sector and the cost of national coverage was prohibitive. As a result, there was a scaled down response based on MSS coverage of the Canadian portion of the Great Lakes watershed and the creation of seamless, bi-national information products for the whole watershed. These products included:

1. An image mosaic of the watershed (eventually displayed in Canada's Museum of Science and Technology) (Guindon, 1997).
2. A land use/land cover product based on portions of approximately 80 Landsat scenes, using a novel scene compositing procedure (Guindon and Edwards, 2002a and 2002b).
3. A proto-type interactive digital image atlas (pre-Google Earth) demonstrating the use of the Great Lakes land use/land cover product, in conjunction with the Digital Chart of the World, to create additional specialized products and accompanying text (Guindon, 1996).
4. Great Lakes Urban Survey.

The Great Lakes Urban Survey explored the integration of a land use/land cover product with demographic data to develop an information base of urban form for major Canadian cities. This information base was then used to assess two indicators related to urban transportation. The first was the sustainability of the transportation network for policy makers and the second was to explore, through travel modeling, alternate urban forms and their impact on travel effort (Zhang et al., 2010).

Wetland Mapping and Monitoring

One would think mapping wetlands would be relatively easy but monitoring them is challenging since they are constantly changing throughout the season. Water elevation changes with surface and subsurface soil saturation dynamics tied to wetland plant growth during a season brings a host of challenges to the wetland mapper. For the Great Lakes, coastal wetlands in their natural state are clearly unique because they are influenced by lake water levels that rise and fall to either climate or weather-related events such as seiches. However, in the Great Lakes water levels have been maintained at a relatively constant level to facilitate shipping, leading to significant unintended consequences. This issue is discussed in more detail below.

Wetland mapping and monitoring is a specialized form of land cover mapping that is well covered in the literature. Koeln et al (1988) used Landsat to map wetlands and other land cover types for Ducks Unlimited, starting in the GLB. Recently, Mahdianpari et al (2020) produced the most accurate, comprehensive, systematic, 40-year literature review for North American wetland remote sensing. Tiner (2015) listed over 1400 citations while Guo et al (2017) identified 5719 papers in their review of wetland remote sensing. Many hundreds more have been published and summarized in the literature since, including many localized highly focused studies in the GLB. (White et al, 2020; Battaglia et al, 2021; Mirmazloumi et al, 2021)

Most papers on remote sensing of wetlands begin by listing some of the many reasons why wetlands are important. Those commonly found in the studies reviewed for this paper include storage of water, storage of sediment, water purification and filtering of contaminants, flood mitigation, erosion control and shoreline stabilization, carbon sequestration, wildlife habitat, recreation, habitat for migratory species and the list could go on. In discussing the importance of wetlands to Canada, one paper noted that "14% of Canada is covered by wetlands, which corresponds to approximately 25% of the world's wetlands." (Dabboor et al, 2022) While these studies have detailed the importance of wetlands, it has also been noted that wetlands have been "drained extensively worldwide to increase acreage for cultivation of crops and accommodate expansion of human settlement." (Gallant, 2015) The human threat to wetlands has continued and forms a focus for some of the recent assessments of remote sensing discussed here.

While wetlands are important on many levels, it is also true that wetlands are inherently difficult to monitor, whether using remote sensing, field methods, or some combination of the two. Wetlands are often difficult to access, making field verification and sampling difficult, although today's location technologies do make it possible to return to within a few centimetres to study the same spot previously visited. In addition to inaccessibility, wetlands tend to have a wide variety of differing vegetation types, especially as one moves from water to upland vegetation including forest cover. Furthermore, these vegetation types are often difficult to distinguish from above and they tend to vary as water levels rise and fall. Further complicating the problem, many wetlands are small and isolated, rendering them invisible to many remote sensing systems.

There are also other factors that the user of remote sensing must consider. These include the vegetation or cover types that must be identified and mapped, the accuracy needed, and the minimum mapping unit for which information is required. One must also consider the repeatability expected by the user, the availability of the required remote sensing data that is indicated, and the skills of those interpreting and processing the data. Complicating everything is the cost. (White et al, 2020).

Cowardin (1979) of the U.S. Fish & Wildlife Service, created the first 'modern' National Wetland Inventory (NWI) map system based on a snapshot in time using interpreted, high-altitude stereo colour infrared (CIR) aerial photography for most of the US. The scale of the program was massive. The resulting interpretations were not photogrammetrically placed on topographic maps due to cost. This led to polygon map position errors in later years when GIS emerged as an organizing tool. Minnesota was one of the first states to have their original NWI maps digitized and made available on the internet in the 1990s. However, when the state NWI was updated beginning in 2011 (Kloiber et al, 2014), the entire state had to be redone due to not only the positional accuracies noted but, more importantly, the approach to mapping wetlands had changed because of many technology factors. The six factors identified were:

1) Aerial film had been replaced by digital aerial mapping cameras.
2) Digital mapping cameras were meeting the resolution of aerial film.

3) Stereo aerial image interpretation was still not efficient for low-cost large area mapping.
4) LiDAR was used extensively to help better define upland vs wetland polygons using Topographic Positioning Indices (TPI).
5) GIS systems allowed many additional GIS layers to be used as reference layers.
6) Image Object software (e.g., eCognition) was used to help make a semi-automated approach for delineating and identifying wetland types as compared to using an orthoimage in a GIS.

In retrospect, the new Minnesota NWI is an improvement when compared to the 1980's era NWI, but it is still a snapshot in time, and it was very expensive. The project took nearly ten years and over seven million dollars to complete. This project was one of the few statewide NWI updates done in the last two decades. Other NWI mapping projects are much smaller in area due to cost and complexity.

For the reasons noted above, other, more dynamic, and cost effective, automated wetland mapping approaches are being developed as discussed in Section 5, Great Lakes Restoration Initiative (GLRI).

One might expect that these complicating factors might discourage wetland monitoring with remote sensing; but they do not. Wetlands are now seen as so important to our environment that they **must** be monitored and monitored well. The balance of this section outlines how some of the tools available in today's remote sensing toolbox have been used and with what result.

The Introduction of LiDAR

LiDAR has long been used for a variety of applications, beginning in the 1970s with work in bathymetry by Bob O'Neil at CCRS who "successfully demonstrated lidar bathymetry and created an operational system to collect, process, and disseminate results." (Ryerson, 2019) LiDAR for bathymetry has long been a commercial offering of Teledyne-Optech. https://www.teledyneoptech.com/en/applications/coastal-and-marine/bathymetry/

The introduction of LiDAR data to the study of elevation related to wetlands in the late 1990s and early 2000s contributed to more accurate digital elevation models which in turn led to better identification of wetlands (especially smaller ones) and improved location of their boundaries. (Hogg and Holland, 2008) Their project was undertaken by the Ontario Ministry of Natural Resources (OMNR) and Ducks Unlimited Canada (DUC) to develop an efficient and accurate methodology for inventorying wetlands. They have shown that Digital Elevation Models (DEMs) are an important factor for wetland identification and boundary delineation. The work with LiDAR illustrated the limitations of the provincial DEM. Simply stated, not being able to identify small changes in topographic relief can lead to significant errors – and significant changes in vegetation occur with just millimeters difference in elevation.

Hogg and Holland (2008) explored "whether wetland mapping derived from bare-earth light detection and ranging (LiDAR) data would overcome the limitations of the provincial DEM." They applied a similar approach to wetland mapping with the two methods of accounting for elevation. They used one hundred aerial-photo-interpreted sample plots to assess how well upland was separated from wetland. The study concluded that LiDAR showed a "significant improvement over the provincial DEM for mapping wetlands, improving overall mapping accuracy from 76% to 84%."

Early research demonstrated that LiDAR could be used to do forest inventories (Lim et al, 2003; Lim, 2006), and today Lidar is being used to do so on a commercial basis.

Species at Risk and Wildlife Habitat

Habitat can be thought as food, water and shelter for any animal. Another way to think of habitat is as the combination of the physical, chemical and biological features of the environment over space and time. Using remote sensing in the GLB to map wildlife habitat is especially challenging since many birds and animals move from place to place. Habitat loss from a variety of factors, including agricultural development, oil and gas exploration, urbanization, and climate change, is contributing to the loss of biodiversity, species at risk, habitat degradation and fragmentation. In 1992 the United Nations Convention on Biological Diversity (CBD) was created to promote the protection of biodiversity. In response to the CBD Canada created the Federal Species at Risk Act (SARA) in 1992. In 2010 the US funded the GLRI focusing on five key areas: 1) toxic substances and areas of concern; 2) invasive species; 3) nonpoint source pollution impacts on nearshore health; 4) habitats and species; 5) foundations for future restoration actions (Great Lakes Restoration Initiative, 2019). Aerial, satellite or UAV imagery can be used as a tool to monitor habitat loss, and critical habitat for species at risk.(Young, E.R., 2009 and https://eros.usgs.gov/doi-remote-sensing-activities/2016/fws/great-lakes-remote-sensing-coastal-wetlands)

An early example of the use of aerial imagery for species at risk came in 2004 when the U.S. Fish & Wildlife Service began taking oblique videos and large format colour aerial photographs over Piping Plover (*Charadrius melodus*) historic and active nesting sites across the U.S. side of the Great Lakes coastline. The Piping Plover is an endangered bird species that nest and feed on flat, sandy beaches. Many of the coastal beaches traditionally used by Piping Plovers for nesting have been lost to commercial, residential, and recreational developments. The imagery was used to document change during the summer of 2004 (Huberty, Personal Communication April 2, 2022). Dynamic range maps such as this eBird example (https://ebird.org/science/status-and-trends/pipplo/range-map-non-breeding) for Piping Plovers help define the best time to monitor coastlines with aerial and satellite imagery. From these image sources, the physical features such as flatness, water levels tied to distance to shrubs and trees (perches for predators) as well as human activity can help further refine the best habitat for these birds.

In a more recent example, aerial photographs were used to digitize potential nesting habitat for snapping turtles (Chelydra serpentina) in Cootes Paradise Marsh in Hamilton, Ontario, from 1934 to 2010. The objective was to quantify the changes in potential nesting habitat. Results suggest that there was a 50% decline in potential nesting habitat from 1934-2010 (Picsak and Chow-Fraser, 2019). A third example saw aerial imagery from 1931-2015 used to digitize and classify the available habitat for herpetofauna in Point Peele National Park on Lake Erie, which has experienced the extinction of five amphibian and six snake species. Change detection showed that there had been a decline in both habitat diversity and aquatic connectivity from 1934 to 2010. In addition, results suggest that marsh consisting of graminoid and forb shallow marsh mixed with water transitioned to being dominated by cattails, resulting in changes to vital breeding, foraging, and overwintering habitat. (Markle, Chow-Fraser, Chow-Fraser, 2018) Satellite imagery has also been widely used to monitor critical habitat and species are risk in the Great Lakes. A combination of aerial imagery and Sentinel-2 data were used to develop a method to map vernal pools in the southeastern Georgian Bay area. Vernal pools are small, temporary wetlands, and are critical habitat for herpetofauna and are particularly sensitive to climate change and habitat fragmentation (Luymes and Chow-Fraser, 2021).

Another, similar recent example of population decline attributed to habitat loss and invasive species is with the Black Tern (*Chlidonias niger*) nesting in the Lake St. Clair Delta. These birds build floating nests using bulrushes (*Schoenoplectus*) on the outer fringes of the delta. Since the early 1990s the number of black tern colonies has dropped nearly 90 percent. (Wyman and Cuthbert, 2017 and https://greatlakesecho.org/2018/01/17/black-tern-numbers-plummet-invasives-largely-to-blame/)

Invasive species

As introduced in the previous section, invasive species pose a serious threat to aquatic ecosystems such as the Great Lakes, causing loss of biodiversity (Houlahan and Findlay 2004), altering hydrology (Ayers et al., 2004) and sediment nutrient cycling (Templer et al., 1998), and they negatively influence the economy (Pimentel et al., 2000; Jackson et al., 2002). Non-native aquatic species in the Great Lakes have been reported since the early 1800’s (Sturtevant and Lower, 2019). To date, there have been three large waves of invasive species introduced to the Great Lakes. The most recent wave occurred from approximately 1959-2001, saw species being introduced at a rate of 1.81 per year, the highest on record. This large increase was attributed to ballast water (Sturtevant and Lower, 2019).

An early project on the use of remote sensing for analysis of invasive species began at the University of Wisconsin and was spun off to the Wisconsin Department of Natural Resources (WDNR). The project involved the use of Landsat imagery for mapping reed canary grass (*Phalaris arundinacea*). The grass is a major threat to natural wetlands since it is one of the first plants to sprout in the spring, forms large single-species stands, and out-competes most native species. (Hatch and Bernthal, 2008)

Identifying invasive species early on and monitoring the expansion and the effectiveness of control measures such as herbicide spray is crucial to minimize their spread. Remote sensing has been shown to be effective at identifying and monitoring several aquatic invasive species.

One often-cited use of remote sensing for invasive species detection and monitoring is for *Phragmites australis*. Bourgeau-Chavez et al. (2013) used ALOS PALSAR imagery to create a baseline map of Phragmites for the entire GLB. In another study, Landsat, ALOS PALSAR, Southwestern Ontario Orthophotogrpahy project (SWOOP), high resolution colour imagery and unoccupied aerial vehicle (UAV) images were compared for Phragmites mapping. Results showed UAV imagery had the highest accuracy for mapping Phragmites but was only able to cover a small area at a time. It was concluded that UAV imagery was not a practical approach for large-area mapping (Marcaccio and Chow-Fraser, 2016).

The most current map of Phragmites and other species across the basin was produced from the use of a combination of multi-date SAR and optical data (Bourgeau-Chavez et al. 2015). This circa 2010 map is available to view and may be downloaded on request from the Michigan Tech Research Institute (MTRI). (http://geodjango.mtri.org/coastal-wetlands/). (See Figure 2.)

Significant projects to control invasive plants have occurred in the years since the 2010 map was produced. Efforts like the GLRI have contributed millions of dollars of funding with the hope of halting *Phragmites* spead. A multitude of smaller *Phragmites* mitigation projects have also taken place, with a variety of treatment methods being used. While the combinations of herbicide, mowing, and burning have served as effective management techniques in some areas, the invasive *Phragmites* has continued to spread to new areas when left unchecked. To more fully illustrate the value and accuracy of using remote sensing for the analysis of invasive species, as well as other classes of vegetation, the balance of this section provides considerable detail on both how remote sensing data are used and with what result.

The best approach to date for monitoring field or local scale *Phragmites*[vii] treatment and control is the use of high resolution UAV or 8 band sub-meter Worldview data. Such an effort was undertaken in Saginaw Bay, Michigan where several locations were subject to treatment and control for invasive *Phragmites* between 2016 and 2018. Worldview-2 data were used to track treatment success, status, and what was regrowing. The map in Figure 3 shows the treatment areas in orange and green polygons. Below are a few examples of the capability of mapping with Worldview-2. It includes mapping standing dead *Phragmites* (detritus on legend); mixed *Phragmites* (< 50% *Phragmites* mixed with other wetland species); *Phragmites*-dominant areas (> 50% *Phragmites* dominant); as well as *Typha*, wet meadow and emergent classes.

These maps are being used by the Saginaw Bay Cooperative Invasive Species Management Area (SB-CISMA) and other stakeholders in applying an adaptive management strategy to the control of Invasive *Phragmites*. A total of 11 areas have been monitored in the field and via Worldview-2 since 2016. Dutch Creek was treated again in the autumn of 2018 where these maps showed a resurgence of *Phragmites* growth (dark purple in the 8/14/2018 map of Figure 4). The maps of Figure 5 were provided to the Bay County person in charge of treatment at that site.

The Saginaw Bay treatment sites included treatments in 2016, 17 and 18 (Table 1), as well as new treatments in the autumn of 2021. The Vanderbilt, Saganing, Hampton and Pine River sites were treated with a mix of glyphosate and imazapyr only in the autumn of 2016. Hampton and Vanderbilt were partially mowed in winter 2017, Pine River was not. Callahan, Delta, Dutch Creek, and Ted Putz Park were treated with glyphosate in the autumn of 2016 followed by winter mowing. JC Airport and Crow Island were treated with glyphosate in the autumn of 2017, and JC airport was mowed in winter 2018. All sites treated with glyphosate alone were followed up with spot treatments of glyphosate the following September/October as needed based on field and UAV or high-resolution satellite reconnaissance.

Overall, 218.09 hectares of *Phragmites* were treated within the over 500-hectare polygon areas between 2016-18, which represents 42% invasion of the total area under surveillance. In 2018, only 24.9 ha (5%) of live *Phragmites* existed in the study polygons, which is a decrease of 89% of live *Phragmites*. The Callahan site proved to be the most difficult; it was an old farm field, heavily invaded by *Phragmites* with only about a 50% reduction. In the autumn of 2018, that site was treated with a stronger mix of glyphosate and imazapyr. This was reduced by about 90% after the autumn 2018 treatment. The Dutch Creek site in Figure 3 was also treated in the autumn of 2018. Follow up satellite reconnaissance (Autumn 2020 imagery) was conducted to determine the effectiveness of the new treatment. The inconsistent availability of cloud-free imagery demonstrates the need for the radar-only classification capability to be further developed (see section 2.1.3).

High resolution data (submeter, e.g., Worldview) are necessary to accurately map the leading edges and extent of invasive *Phragmites* for management. Maps from interpreting Worldview data have been used for GLRI projects for Phragmites control, as well as for projects funded by Michigan Department of Environment, Great Lakes, and Energy (MDNR/EGLE), National Fish and Wildlife Foundation (NFWF), and USFWS. Classification Maps of *Phragmites*, *Typha* and other wetland types were produced for all of the Saginaw Bay coastal zone from Worldview-2 - August 2016 for managers. http://geodjango.mtri.org/coastal-wetlands/ is available to view/download maps.

Such high-resolution mapping allows for targeted treatment, maps for bids and application of aerial spraying vs hand spraying needs (Figure 6). The new grant from Sustain Our Great Lakes (SOGL) via NFWF for control of Phragmites and coastal wetland restoration in Saginaw Bay included field and remote sensing monitoring during the summers of 2021 and 2022. The access to the Worldview-2 imagery from this project for Saginaw Bay in 2020 enabled production of classification maps of where herbicide treatment is needed in both previously treated coastal wetlands and new treatment areas.

Table 1. Summary of pre- and post-treatment Phragmites extent and percent change for all Saginaw Bay treatment sites. Estimates are based on Worldview-2 image classifications using field data for training wetland type and species dominance. All sites were mapped using 2015-16 pre-treatment Worldview-2 imagery. All sites were mapped post-treatment using 2018 imagery. Vanderbilt, Saganing, Hampton and Pine River were treated with a mix of glyphosate and imazapyr in the autumn 2016. Hampton and Vanderbilt were partially mowed in winter 2017. Callahan, Delta, Dutch Creek, and Ted Putz Park were treated with glyphosate in autumn 2016 followed by winter mowing. JC Airport, Crow Island were treated with glyphosate in autumn 2017, and JC airport was mowed in winter. All sites treated with glyphosate were followed up with spot treatments of glyphosate the following autumns as needed.

	Pre-treatment				Post-treatment				
Site	Year	Mapped treatment area (ha)	Mapped as Phragmites (ha)	Percent Phragmites	Year	Mapped treatment area (ha)	Mapped as Phragmites (ha)	Percent Phragmites	Percent change
Callahan	2016	20.72	11.25	54	2018	21.03	5.50	26	-51
Crow Island	2016	71.23	30.20	42	2018	71.21	6.21	9	-79
Delta	2016	0.36	0.27	75	2017	0.34	0.00	0	-100
Dutch Creek	2016	139.59	27.70	20	2018	139.46	7.47	5	-73
Hampton	2016	237.36	127.73	54	2018	237.34	2.65	1	-98
JC Airport	2016	4.98	2.31	46	2018	4.97	0.18	4	-92
Pine River	2016	2.20	0.57	26	2018	2.20	0.00	0	-100
Saganing North	2015	14.48	1.19	8	2018	14.45	0.06	0	-95
Saganing South	2015	0.76	0.21	27	2018	0.76	0.00	0	-100
Ted Putz Park	2015	1.51	0.69	45	2018	1.52	0.02	0	-97
Vanderbilt Park	2016	24.57	15.97	65	2018	24.58	2.78	11	-83
Total		517.8	218.09	42		517.8	24.87	5	-89

Other examples of the use of remote sensing for invasive species, include Unitis (2018), who successfully used multi-temporal (spring, summer, all autumn) Sentinel-1 C-band SAR imagery and RapidEye (5 m resolution, multi-spectral optical imagery) to classify hybrid cattail and other coastal wetland vegetation in St. Mary's River, Lake Michigan. Similarly, Ghioca-Robrecht et al. (2008) used Quickbird (2.4 m resolution optical imagery) in the western basin of Lake Erie to classify emergent invasive plants and found that Phragmites and non-native Typha could be separated, even when the patches were long and narrow.

UAV's are now routinely being used for many mapping purposes including invasive species. For example, UAV imagery also accurately maps hybrid cattail, frogbit, and two submergent species (*Chara* spp. and *Elodea canadensis*) applying the commonly used machine learning classifier Random Forest in Alpena Wildlife Refuge, Lake Michigan. The high resolution of UAV's makes early detection of many aquatic invasive species possible. In summary, invasive species monitoring programs should leverage remote sensing both for early detection and for monitoring growth pre and post treatment.

Algal blooms and subsurface mapping

Cladophora is a genus of reticulated *filamentous Ulvophyceae* (green algae). Wisconsin's nearshore *Cladophora* was mapped using interpretation of high-resolution colour aerial photography. The genus *Cladophora* contains many species that are very hard to tell apart and classify, mainly because of the great variation in their appearances, which is affected by habitat, age and environmental conditions. Early work demonstrated the usefulness of Landsat imagery to identify areas of Cladophora growth in the shallow nearshore waters of Lake Huron (Lekan and Coney, 1982) as part of Cladophora growth modeling efforts (Canale and Auer, 1982).

2004 summer colour aerial photographs were used to map the Wisconsin coastal zone in Lake Michigan for *Cladophora*. The results can be seen with *Cladophora* classification (20% transparent) over aerial photos:
http://re.ssec.wisc.edu/?products=WICoast.100,clad.20&center=43.072,-87.849&zoom=15

Vegetation damage

Following the previously cited early work by Murtha on vegetation damage caused by pollution near Wawa, Ontario, there have been other studies in the GLB. Pitblado and Amiro (1982) assessed Landsat data of the industrially disturbed area surrounding Sudbury, Ontario. They found that zones of damage radiated from where smelters were located. They concluded that "the most satisfactory results were obtained with a vegetation index of relative biomass computed using a red and near infra-red ratio." Pixel classifiers yielded less useful results.

Hall et al (2016) reviewed the use of remote sensing for the assessment of forest pest damage. As in the earlier study by Pitt et al (1997) they concluded that remote sensing tools could augment simple aerial photography, but rarely replace such photography. A detailed assessment of the use of various sensors for a variety of pests encountered in Canada's forests is given in a series of detailed tables that summarize the more than 350 papers cited. As might be expected, the best tool depends on the scale of the questions being asked of the imagery and the requirements of the user of the resulting information. The study concluded that "Aerial survey is the primary tool for mapping the location and severity of forest pest damage, and it will likely continue to be relied upon by the forest health community." The paper closes with a look to where remote sensing might play a role and an assessment of advanced sensors, several of which are discussed in more detail here in Section 5.

5. The Modern Era

Introduction

The modern era is marked by several different but interacting attributes. First is the arrival and better understanding of new technologies: sensors, platforms and analysis tools and how they fit together to respond to the resource manager's requirements. Second, there is now a view of the Great Lakes as a natural and complex system that must be studied as a whole, while also understanding the local environment. These new technologies – radar, drones, LiDAR, and analysis tools, are especially well-suited to both the scale of the Great Lakes as a whole and the need for fine detail for many monitoring and assessment applications. Third, climate change has become top of mind, leading to requirements for change detection and assessment. Fourth, the state and provincial governments have become more involved in the research and development activities leading to faster development and use of the new tools by the resource managers in their respective jurisdictions.

The remainder of this section reviews these new tools and some of the results of their use as well as detailing several basin-wide analyses that highlight the successes to date and potential for the future.

InSAR Applications

The canopy penetration capability of microwaves can result in enhanced backscatter (i.e., the portion of the radar signal that the target redirects directly back towards the radar antenna) from a double-bounce scattering mechanism. This is where the reflected pulse hits the water and then the emergent vegetation and then back to the sensor, which allows for the mapping of flooded vegetation (Brisco, 2014, Bourgeau-Chavez et al. 2013). Recent investigations have shown that, under certain conditions, this SAR response signal from flooded vegetation remains coherent during repeat satellite over-passes (Brisco et al., 2017). Coherence is the fixed relationship between waves in a beam of electromagnetic (EM) radiation. Two wave trains of EM radiation are coherent when they are in phase. That is, they vibrate in unison. In terms of the application to things like radar, the term coherence is also used to describe systems that preserve the phase of the received signal (https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-1-sar/definitions). Coherence is measured from 0 for no coherence to 1 for fully coherent. This can be exploited by interferometric SAR (InSAR) measurements to estimate changes in water levels and water topography (Lu et al, 2008). This application will be described in more detail for several sites in the GLB later in this section. InSAR studies also suggest that coherence change detection (CCD) might be applied to wetland classification and monitoring applications.

Brisco et al (2017) examined wetland vegetation characteristics that led to coherence in RADARSAT-2 InSAR data of an area in the Ottawa River valley with many small wetlands. They determined the annual variation in the coherence of these wetlands using multi-temporal radar data. The results demonstrated that most swamps and marshes maintain coherence throughout the ice-/snow-free time-period for the 24-day repeat cycle of RADARSAT-2. However, open water areas without emergent aquatic vegetation generally do not have suitable coherence for CCD for InSAR water level estimation. They found that wetlands with tree cover exhibit the highest coherence, wetlands with herbaceous cover can exhibit high coherence, but also have a high variability of coherence; and wetlands with shrub cover exhibit high coherence, but variability is intermediate between treed and herbaceous wetlands. From this knowledge a novel image product was developed that combines information about the magnitude of coherence and its variability with radar brightness (backscatter intensity). This product clearly displays the multitude of small wetlands over a wide area. With the interpretation key developed, it is possible to distinguish different wetland types and assess year-to-year changes (Figure 7).

Mohammadimanesh et al (2018) showed that wetlands with flooded vegetation were coherent at all polarizations in X, C, and L-band SAR data and the use of coherence complemented the use of magnitude in classification applications resulting in increased accuracy. The shorter wavelength SAR signals are better for herbaceous wetlands whereas the longer wavelengths are better for woody wetlands. The increasing number of SAR satellites with frequent repeat coverage has enabled this application and ongoing research is further developing this approach. Meisam et al (2021) used Sentinel-1 repeat coverage to produce a multi-year coherence data set for Alberta, which has shown promise for classification of wetlands, determination of hydro-period, and CCD applications for land-cover and wetland change. This approach has been implemented for the GLB and research is on-going on the use of coherence for these applications.

Canada (Department of National Defence, Environment and Climate Change Canada and Natural Resources Canada) and the US (US Fish and Wildlife Service, Environmental Protection

Agency, NOAA, Michigan Tech U, U of Minnesota, SharedGeo, and Minnesota Department of Natural Resources) have a bi-national project in the Great Lakes Basin (GLB) involving the use of geospatial techniques for better wetland mapping and monitoring applications. As part of this collaboration, study sites at Lake St. Clair, Long Point on Lake Erie, and Bay of Quinte on Lake Ontario have all been used for InSAR water level studies.

Recently, Chen et al (2020a) investigated two C-band SAR satellites, RADARSAT-2 and Sentinel-1, to determine if InSAR could be used to characterize water level changes within coastal marshes in Long Point, Ontario, Canada. RADARSAT-2 can image the same area with the same beam mode and incidence angle (revisit time) every 24 days, and Sentinel -1 every 12 days. Satellite images were from 2016-2018 and included a variety of beam modes and polarizations. For RADARSAT-2 there were 27 FQ1W and 20 FQ18W scenes which were quad-polarized, as well as 26 U23W2 scenes which were single polarized (HH). (RADARSAT-2 beam modes are described in https://earth.esa.int/eogateway/documents/20142/0/Radarsat-2-Product-description.pdf/f2783c7b-6a22-cbe4-f4c1-6992f9926dca.) For Sentinel-1 there were 38 1W scenes that were dual polarized (VV and VH). However, only the HH polarization was used to create interferograms and measure coherence for the RADARSAT-2 scenes and VV for the Sentinel-1 scenes because other research has shown that coherence values are highest in HH, following that VV, and then HV and VH (Hong et al., 2010). An interferogram is a pattern formed by wave interference, especially one represented in a photograph or diagram. A D-InSAR processing was applied for all image pairs that had the same polarization and incidence angle to create differential interferograms, measure coherence, and observe phase changes.

There were five key findings from this research. (1) backscatter (σ°) was inversely related to the incidence angles. Since FQ1W had the steepest incidence angle it also had the highest σ°. An example being the difference in the σ° values between Cattail/Phragmites and grass increased as the incidence angle became steeper for the HH polarization. (2) Coherence values were higher when the revisit time between two InSAR pairs was shorter. For instance, U23W2 coherence values for Cattail/Phragmites were 0.8 and 0.7 from June – August when the revisit time was 24 days. Coherence values declined to 0.3 for Cattail/Phragmites and 0.2 for grass when the revisit time was 48 days. (3) RADARSAT-2 beam modes with HH polarization were better able to maintain coherence compared to Sentinel-1 with the VV polarization. It is important to note, that coherence values from both C-band satellites differed based on type of vegetation, polarization, resolution, incidence angle, revisit time, timing of the growing season, and water level. (4) When Chen et al. 2020a compared InSAR water level measurements to those from in-situ water level loggers the degree of correlation varied based on site location, vegetation type, sensor parameters, and water flow conditions. All beam modes had both positive and negative correlations with in-situ measurements. Thus, further research is needed to better understand InSAR results in coastal wetlands. (5) When large changes in water level occurred (up to 40 cm) in areas that had good coherence, phase unwrapping was difficult, indicating that C-band SAR is not suitable for detecting large water level changes within wetlands often observed in the Great Lakes.

Chen et al. 2020b expanded their InSAR research in Great Lakes coastal wetlands by investigating the effects of wavelength and polarization on InSAR measurements by comparing three different SAR satellites, TerraSAR-X, RADARSAR-2 and ALOS-2 in the Bay of Quinte, Ontario. Longer wavelengths are able to penetrate vegetation canopies to a greater degree allowing for the detection of emergent herbaceous or woody wetland vegetation and results in double-bounce backscatter to the satellite (Hess et al. 1990, Townsend, 2002, Touzi, 2004). Past research also suggests that longer SAR wavelengths are better suited for InSAR monitoring compared to shorter wavelengths like X-band and C-band because coherence is more stable and can be maintained over longer time periods (Lu et al. 2005; Wdowinski et al. 2008; Kim et al. 2013; Yuan et al. 2017). Of the three satellites in this study, TerraSAR-X had the shortest wavelength (3.1 cm), followed by RADARSAT-2 (5.6 cm), and ALOS-2 (24 cm). To evaluate different polarizations, coherence from TerraSAR-X and ALOS-2 was generated for both HH and HV polarizations, and from RADARSAT-2 HH, HV, and VV. Twenty TerraSAR-X 2016 images with StripFar-005 or StripFar-012 modes were included, as well as 88 RADARSAT-2 images from 2016-2018 from FQ5W, FQ17W, U7W2 and U22W2 modes, and two ALOS-2 FBDR scenes from Stripmap Fine Beam mode on May 20 and August 26, 2018.

Some results for the Bay of Quinte analysis were consistent with those observed in Long Point, while others added additional knowledge to better understand how InSAR can be used to monitor water level changes in coastal wetlands. The main conclusions from this research are: (1) Trends in water level changes were correctly measured with InSAR but large root mean square errors (RMSE) occurred, suggesting the water level changes were underestimated. Large changes in water levels over short time periods were not able to be measured by sparse InSAR observations (long revisit period) such as TerraSAR-X (11 days) and RADARSAT-2 (24 days). In addition, changes in water level and phenology during the growing season affected the quality of the interferograms. For instance, from June-August there were low water levels which decreased double-bound backscatter so coherence was not able to be measured (Chen et al, 2020b). (2) The length of the revisit time was an important factor for maintaining coherence in the wetlands in the Bay of Quinte. To evaluate the affect of revisit time the authors compared TerraSAR-X data with a revisit time of 11, 22 days, and 33 days, and RADARSAT-2 data with a revisit time of 24 days and 48 days. For all example's coherence was inversely related to revisit time (Chen et al, 2020b). (3) In the Bay of Quinte σ° was also stronger with steeper incidence angles. However, higher resolution SAR imagery appears to be more important for coherence and the quality of the interferograms compared to incidence angle and resulted in a smaller RMSE value when compared to in-situ water levels. To illustrate this, 2018 RADARSAT-2 FQ17 data (shallow incidence angle) had a lower RMSE values from the correlation analysis compared to FQ5 data (steep incidence angle) (Chen et al, 2020b). (4) Differences in coherence were observed based on vegetation type, polarization, revisit time, and wavelength. When coherence was compared between TerraSAR-X and RADARSAT-2, the highest values were observed in marshes that contained mostly cattails for all four beam modes and the two TerraSAR-X beam modes. Swamps had the second highest values for coherence, and shallow water the lowest. When coherence values for TerraSAR-X and RADARASAT-2 were compared using the same revisit time for the same type of wetland, RADARSAT-2 was always higher. When X-band and C-band InSAR pairs were compared in marsh, C-band with HH polarization resulted in the highest coherence values, followed by VV polarization, and HV. For example, the FQ17 RADARSAT-2 beam mode had average coherence values of 0.65, 0.4 and 0.38 from the HH polarization for marsh, swamp and shallow water compared to 0.48, 0.29, and 0.3 from HV polarization, 0.51, 0.35 and 0.3 from the VV polarization. While the authors were not able to directly compare a time series of L-band data with X and C-band due to lack of available ALOS-2 InSAR pairs, when coherence was measured between the two ALOS-2 images, results showed coherence was maintained for the longest time period for both HH and HV polarizations. In contrast to C-band, swamp had the highest coherence values (0.68), then marsh (0.43), and shallow water (0.36) (Chen et al, 2020b).

Results for InSAR analyses at Lake St. Clair showed complementary findings. A series of gauges were installed within the wetlands of the St. Clair delta, some of which were within diked areas which have regulated water levels and thus their water levels are not represented by open lake NOAA gauges. Three dominant emergent wetlands were the focus of this work with increasing stem density, height and biomass (*Schoenoplectus spp., Typha spp.* and *Phragmites australis – invasive variety*). (See Figure 8.)

Three Radarsat-2 FQ4 images were collected on July 17, 2013, September 3 and September 27, 2013 with less than 12 cm water level change between dates. We found the *Typha* sites to exhibit the double bounce scattering necessary for InSAR to work in wetlands and they also showed the highest coherence of all the wetland sites evaluated (Table 2). The *Schoenoplectus* sites showed double bounce scattering at C-band, but did not show high coherence between image dates which we attributed to their sparse and thin nature and the fact that they are more likely to be affected by wind (Figure 9, Table 2). Wind measurements were, on average 3 mph on July17, 13 mph on September 3 and 2 mph on September 27. Assessment of the two less windy dates had water level results that were within the confidence interval that can be expected with any interferogram pair (within $\pm \pi$, in our case $\lambda/2 = 2.8$ cm). The unwrapped phase results showed that for the most part our changes in wetland water levels fall within the 2.8cm confidence interval. All of the Typha sites outside of the diked area had fair to good agreement with the change in water level from the Algonac NOAA gauge station and the change from the InSAR pair (Table 2). The change was lower for the InSAR pair in all cases. Note that the within wetland change measurements in the un-diked *Schoenoplectus* sites were 5 to 7.5 cm lower than the NOAA gauge change. Thus, in wetland sampling allows for the best measure to compare to InSAR. *Typha* within the diked area had in situ water level changes of 1-1.5 cm and thus the phase unwrapping for the un-diked areas was not suitable for these sites within the dike. The *Schoenoplectus* sites had gauges within the wetlands which corresponded best with the InSAR water level changes despite not showing high coherence. This difference was sometimes greater than what InSAR predicted and sometimes lower (Table 2). *Phragmites* sites were often dry during the 2013 season, and were found too dense in most cases for penetration by the C-band wavelength. However, we did find the site within the diked area to the InSAR water level comparison close to the confidence interval of 2.8 cm. Further work with L-band SAR and *Phragmites* is suggested.

Lastly, the *Typha* sites showed high coherence and double bounce (red, yellow – volume and double) on the 17 July 2013 date but on the second date some of the *Typha* sites had a dominant scattering mechanism of surface bounce (blue, Figure 9). We used the 2013 observations and additional field and Radarsat-2 data from 2014-16 to further investigate this lack of double bounce from *Typha* that occurs in some instances. We found that commonly used decomposition approaches (e.g. Freeman Durden) do not always correctly classify inundated wetland vegetation as having prominent double-bounce scattering components at C-band at incidence angles less than 30. We've found this to be due to an apparent abrupt change in co-pol phase difference (CPD) that occurs around the Brewster angle of the emergent vegetation (Atwood et al. 2020). Dependence of CPD on incidence angle and seasonal changes, e.g. senescence, were found. Additional analyses have shown the anomalies to be further complicated by the tilt (typically due to wind) of the vegetation (Ahern et al. in review). Care should be taken in interpreting commonly used decompositions that explicitly separate the backscatter intensity due to the dominant scattering mechanisms based on a threshold of CPD.

Table 2. Comparison of coherence and InSAR changes to water level gauges at the various wetland dominant sites both in diked and non-diked areas. The Algonac NOAA gauge change was 11.5 cm between July 17 and Sept 27, 2013.

Num	**Cover Type**	**Diked/ Not Diked**	**Pixel Count**	**Coherence**	**InSAR Change (cm)**	**Within Wetland or NOAA Gauge Change (cm)**	**Difference**
1	*Typha*	Diked	10488	0.46	5.49	1	4.49
3	*Phragmites*	Diked	3293	0.11	6.97	9.8	-2.83
4	*Typha*	Diked	1850	0.23	5.58	1.5	4.08
5	*Schoenoplectus*	Not Diked	646	0.13	5.16	5.6	-0.44
6	*Schoenoplectus*	Not Diked	493	0.16	7.5	6.3	1.2
7	*Schoenoplectus*	Not Diked	563	0.08	3.38	4.2	-0.82
8	*Schoenoplectus*	Not Diked	511	0.13	0.94	3.8	-2.86
9	*Typha*	Not Diked	2404	0.29	7.86	11.5	-3.64
10	*Typha*	Not Diked	2823	0.28	10.18	11.5	-1.32
11	*Typha*	Not Diked	4127	0.36	7.93	11.5	-3.57
12	*Typha*	Not Diked	4109	0.25	7.38	11.5	-4.12
13	*Typha*	Not Diked	5502	0.47	10.38	11.5	-1.12
14	*Typha*	Not Diked	3731	0.44	8.31	11.5	-3.19
15	*Typha*	Not Diked	3813	0.42	8.7	11.5	-2.8
16	*Typha*	Not Diked	5662	0.52	8.97	11.5	-2.53
17	*Typha*	Not Diked	7650	0.55	9.2	11.5	-2.3
18	*Typha*	Not Diked	5199	0.56	9.57	11.5	-1.93
19	*Typha*	Not Diked	5693	0.53	10.19	11.5	-1.31
20	*Typha*	Not Diked	8778	0.5	8.93	11.5	-2.57

Drones

As their capabilities have increased, UAVs have become a more common tool for helping to map and assess both terrestrial and aquatic ecosystems in the Great Lakes. Marcaccio et al. 2016 used natural color optical imagery from multi-rotor and fixed wing systems to identify marsh habitats, including locations of invasive *Phragmites*. Brooks et al. 2021 demonstrate the utility of natural color UAV sensing for identifying *Phragmites* in treated sites in the Great Lakes basin. Brooks 2020 and Brooks et al. 2019 showed how multispectral profile data collection and multispectral imagery collected via UAV could be used to reliably identify the invasive submerged aquatic plant Eurasian watermilfoil (EWM, *Myriophyllum spicatum*).

UAV-enabled sensing has also been documented as an important part of more comprehensive tracking of changes in Great Lakes wetlands (White et al. 2020). It has also been recommended as part of citizen-science programs for monitoring coastal change due to lake level changes (Theuerkauf et al. 2022).

Basin Wide Applications and Big Data

There are other human-induced threats to wetlands that are a result of unintended consequences of our activities. Nowhere is this more readily observed than in the Great Lakes where water levels have been maintained at a constant level to facilitate shipping. A number of studies were carried out to assess the effects of water regulation. (Wilcox and Bateman, unpublished report; Wilcox and Xie, 2005) In 2018 the Great Lakes-St. Lawrence River Adaptive Management (GLAM) Committee wanted to track changes in Great Lakes wetlands to determine how and if the changes could be related to changes in the Great Lakes water level management. Meadow marsh vegetation was selected for the assessment of the usefulness of remote sensing to monitor change. (White et al, 2020) Given the minimum mapping unit, size of the areas to be monitored, problems of accessibility, and accuracy required, the authors identified human photo interpretation of simple aerial imagery acquired by a drone as the ideal solution to meet the need for detailed and accurate information on meadow marsh vegetation. (White et al, 2020)

While very localized information can be obtained with remote sensing, there have been successful studies that monitor wetlands across the entire basin. It is not surprising that the most successful of these studies use a variety of sensors and analysis tools and that those engaged in doing the studies are well versed in the biology and environments within which they are working.

Bourgeau-Chavez and her colleagues used three seasons of Landsat TM imagery fused with PALSAR imagery in a project that they describe in great detail. (Bourgeau-Chavez, 2015) They found that for upland vegetation Landsat imagery was sufficient, however, the SAR data provided information on inundation of the vegetation which allowed for distinction of the coastal wetlands. The original focus of the study was the mapping of invasive species - *Phragmites*. In the end, with the approach they developed, they could accurately map wetland classes and surrounding land use 10 km in from the shore for the entire basin – an area of 9,056,410 ha. A minimum mapping unit of 0.2 ha was used for the project. While "the overall accuracy for the coastal Great Lakes maps was 94%, with a range from 86% to 96% overall accuracy by lake basin (Huron, Ontario, Michigan, Erie, Superior)" (Bourgeau-Chavez et al, 2015), the accuracies within certain wetland classes were lower. Even so, the accuracies obtained compare favourably with those obtained elsewhere.

Bourgeau-Chavez et al (2017) have since extended the mapping through various NASA grants, first for the Upper peninsula and later for Michigan’s lower peninsula and most recently for the rest of the basin (Battaglia et al., in prep). Because there was no field data for all the regions a form of “transfer learning” was used and as a result the accuracy of the basin classes beyond Michigan and the coastal zone is somewhat lower. What was done was not exactly what the literature calls "transfer learning" - machine learning that stores knowledge gained while solving one problem and applying it to a different but related problem. They used spectral reflectance to determine what training data would be used for new areas, matching up the greenness from the image dates, which could vary drastically from one area of interest to the next. These maps are viewable on https://geodjango.mtri.org/coastal-wetlands/ and one can request data there. There is also a link on that page to a partial basin circa 2017 map update https://www.sciencebase.gov/catalog/item/5d0bb792e4b0e3d3116204c4

Recent work has continued to show the value of satellite imagery for identifying *Cladophora* extent (Shuchman et al. 2013). This work enabled studying the changes in *Cladophora* extent over time and its likely relationship to increased water clarity due to the introduction of invasive *Dreissenid* mussels (Brooks et al, 2015); this work covered the nearshore areas of Lakes Michigan, Huron, Erie, and Ontario.

Dr. Shuchman’s work was instrumental in establishing that widely available, daily, moderate resolution satellite imagery could be used to identify the three colour producing agents (CPAs) of freshwater (chlorophyll, dissolved organic carbon, and suspended minerals) in the open waters of the Great Lakes (Pozdnyakov et al. 2005, Shuchman et al. 2013). This enabled more comprehensive identification of harmful algal bloom (HAB) extent in the Great Lakes, including going back 20 years in time to look at trends in frequency and extent (Sayers et al. 2020).

Canadian Space Agency SOAR program

The SOAR program designed to promote the new Radarsat 2 satellite was an early binational remote sensing project. The University of Minnesota teamed up with CCRS to research “The integration of optical, topographic, and radar data for wetland mapping in northern Minnesota”. https://experts.umn.edu/en/publications/the-integration-of-optical-topographic-and-radar-data-for-wetland The classifier was able to improve wetland vs. upland delineations with the addition of Radarsat 2 data. This was significant not only for the research but it also represented the start of continued collaboration in future years.

Great Lakes Restoration Initiative (GLRI)

2010 was the start of a $300 million bipartisan investment by the U.S. to help restore the Great Lakes System. Initially, a broad range of remote sensing projects (worth eight million dollars) was proposed by the U.S. Fish & Wildlife Service to map wetlands, habitats and invasive species. The large list was narrowed down to one innovative project using L-band Radar from PALSAR.

Michigan Tech Research Institute led this innovative project to map coastal invasive Phragmites (Phragmites australis) on the U.S. side using the L-band Japanese Radar Satellite – PALSAR. The objective was twofold: 1) establish a baseline to measure future expansion across the Great Lakes System; 2) provide field managers a map to find and eradicate infestations. See the following sites:
https://www.mtu.edu/mtri/research/project-areas/environmental/wetlands/monitoring-phragmites/maps/ and
https://events.mtu.edu/event/the_role_of_satellite_derived_information_in_the_restoration_of_the_great_lakes

In 2016, additional GLRI funding was obtained to build a cross border collaboration tapping into submeter commercial optical and Radarsat-2 imagery for the Great Lakes Basin (GLB). This project was granted access to the MAXAR DigitalGlobe imagery catalog via the National Geospatial-intelligence Agency's (NGA) NEXTVIEW program. (https://www.maxar.com/products/global-enhanced-GEOINT-delivery) In addition, monthly MAXAR Radarsat 2 imagery was also acquired over a dozen sites across the basin for six years via the NorthernView program with NGA. (The NEXTVIEW program dates back to the Commercial Remote Sensing Space Program (CRSSP) mentioned previously.)

The collaboration was also able to gain a supercomputing grant from the Great Lakes Consortium for Petascale Computing (http://www.greatlakesconsortium.org/) to access the National Science Foundation (NSF) Blue Waters Supercomputer. Once one of the top ten supercomputers on the planet, it was decommissioned in 2021. This part of the project was led by SharedGeo (Battaglia et al. 2021) in collaboration with the NSF funded, University of Minnesota, Polar Geospatial Center (PGC) (https://www.pgc.umn.edu/). PGC developed the procedures for downloading and processing petabytes of DigitalGlobe submeter, stereo imagery to make two-meter surface Digital Elevation Models (DEM) for the polar regions of the planet. Multi-temporal two-meter DEM surface models were also generated for the entire GLB by PGC and SharedGeo thus demonstrating the potential for multi-temporal, submeter satellite mapping at a massive scale. Credit also goes to the Byrd Center at Ohio State University which developed SETSM software to process the MAXAR stereo satellite imagery in Blue Waters.

MTRI was also instrumental for using both the MAXAR optical and radar imagery to better map coastal wetlands across the basin. Working with NRCAN and ECCC, MTRI was able to implement many of the applications highlighted in the previous InSAR section. Monthly water inundation and flooded vegetation maps were generated over the pilot sites across the basin. Detailed, species level, annual, raster-based, wetland classifications were also generated over the pilot sites by combining the MAXAR optical and Radarsat 2 imagery (Battaglia et al. 2021).

Using the surface DEM's as a height discriminator for open water, emergent, scrub-shrub and forested wetlands, the University of Minnesota, Remote Sensing and Geospatial Analysis Laboratory was able to develop an automated image object approach for a simplified, wetland classifications for the MAXAR stereo, optical scenes over the pilot areas as well. This approach shows promise at creating metrics of change at a higher frequency since it does not rely on training sets and field verification.

The end result was the establishment of GLARS – the Great Lakes Alliance for Remote Sensing (glars.org) where the GLRI data products can be accessed and a foundation was laid for future Great Lakes remote sensing, binational programs.

6.0. The Future

The future of remote sensing in the Great Lakes has the potential to lead to better resource management and a healthier set of lakes, all while demonstrating the value of cross-border cooperation and collaboration.

We are already seeing, as this paper demonstrates, cooperation and collaboration between government agencies and academe from many different jurisdictions on both sides of the border. As the return on investment of cooperation is further demonstrated we expect to see even more cooperation at many levels.

Basin-wide monitoring programs have been shown to be possible and effective in generating useful information at the required accuracies. We expect to see more such basin-wide applications. We also anticipate much broader use of imagery from drones to supplement field work to inform our interpretation and assess accuracies. We also anticipate the use of higher spatial and spectral resolution imagery, be it optical, LiDAR or radar. This in turn will lead us to more precise applications of remote sensing.

While the recent emphasis has been on the importance of understanding the Great Lakes as a dynamic system, there will be many more localized studies that will provide useful local information to local decision makers.

As has been documented here, the use of radar data plus optical data from several different data sources at a variety of resolutions and timescales often leads to a better end product. We can expect to see more melding of data sets to improve the accuracies of the information being derived as we also see more use of artificial intelligence and “big data.”

Estimating the impact of climate change will be top-of-mind and responding to climate change can be expected to drive and fund future research. The rapidly changing lake levels of the Great Lakes will continue to be an important climate-related phenomenon to monitor.

With all of the aforementioned benefits it is clear that there will be more users and more projects.

Together the picture painted of the future is bright. What the authors believe will make it even brighter is if there is a formalization of cooperation building on the Great Lakes Alliance for Remote Sensing. Such a formalization should lead to accessible multi-sensor basin-wide data sets, and a central repository for studies, papers and examples of remote sensing applied to issues in the Great Lakes. By so doing knowledge could be more easily shared with and introduced to the user community than is currently the case. Such an approach would see the benefits of applying the technology distributed faster and more widely.

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Figure 1a: Original image approximately 1:130,000 scale Colour Infrared Imagery of the sort used in the Great Lakes Land Use Mapping Project. The enlarged area shows the Grimsby Marina from the upper left corner of the full image. The detail was sufficient for identifying a variety of land use classes.

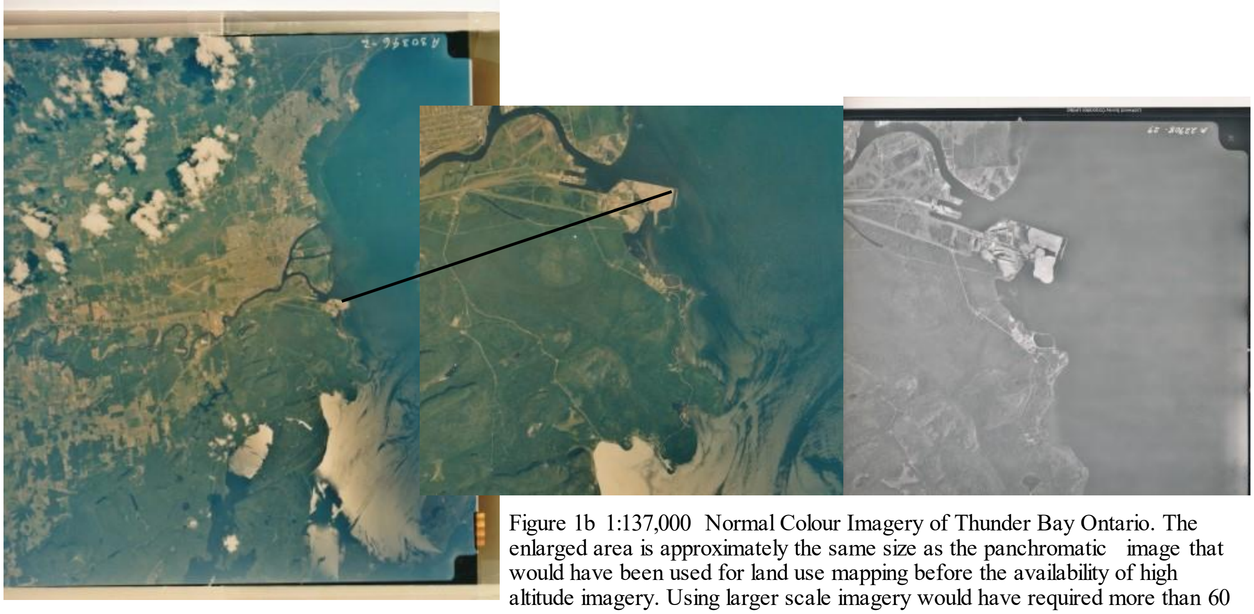

Figure 1b 1:137,000 Normal Colour Imagery of Thunder Bay Ontario. The enlarged area is approximately the same size as the panchromatic image that would have been used for land use mapping before the availability of high altitude imagery. Using larger scale imagery would have required more than 60 times the number of images than we actually used.

Figure 2: Wetland and upland land cover map of the bi-national United States and Canada Great Lakes Basin based on multi-date PALSAR and Landsat-5 in Random Forests

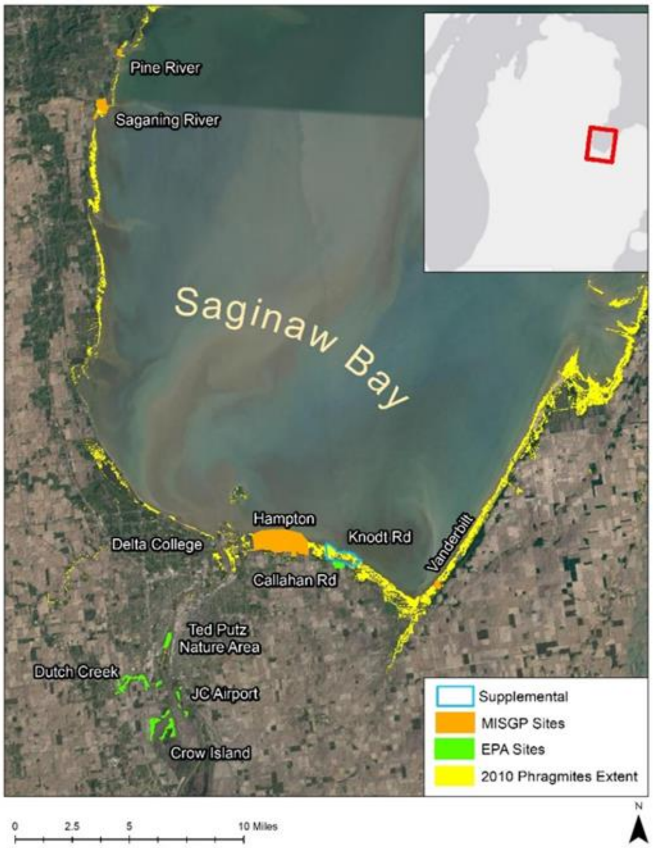

Figure 3: Location of Phragmites treatment areas under monitoring with Worldview-2 and field data collection.

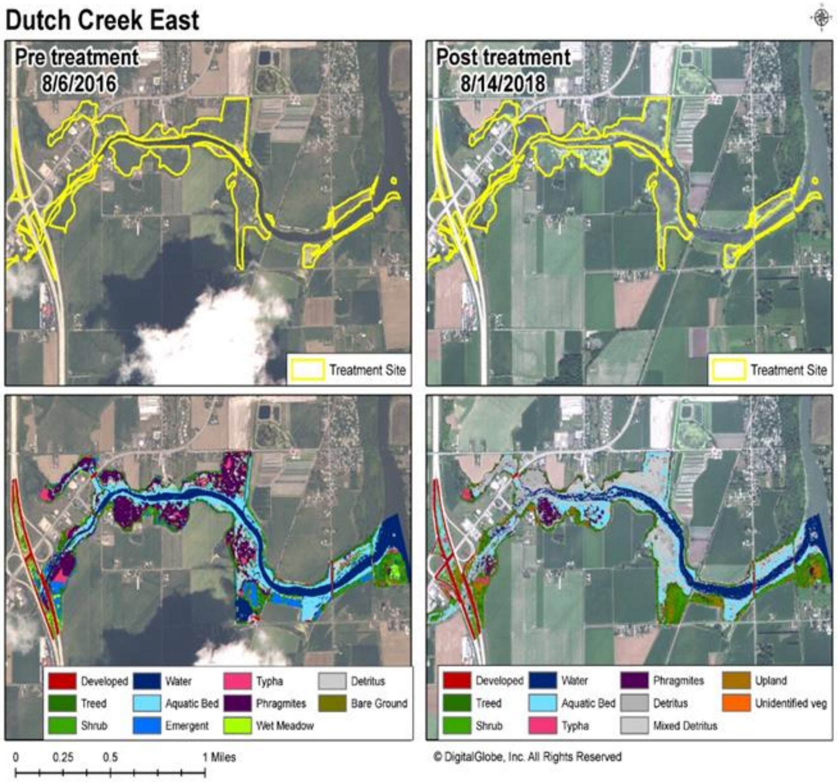

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Figure 4: Worldview-2 Images (top row) and image classifications (bottom row) for the Dutch Creek treatment area from pre-treatment (August 2016) and post-treatment (August 2018).

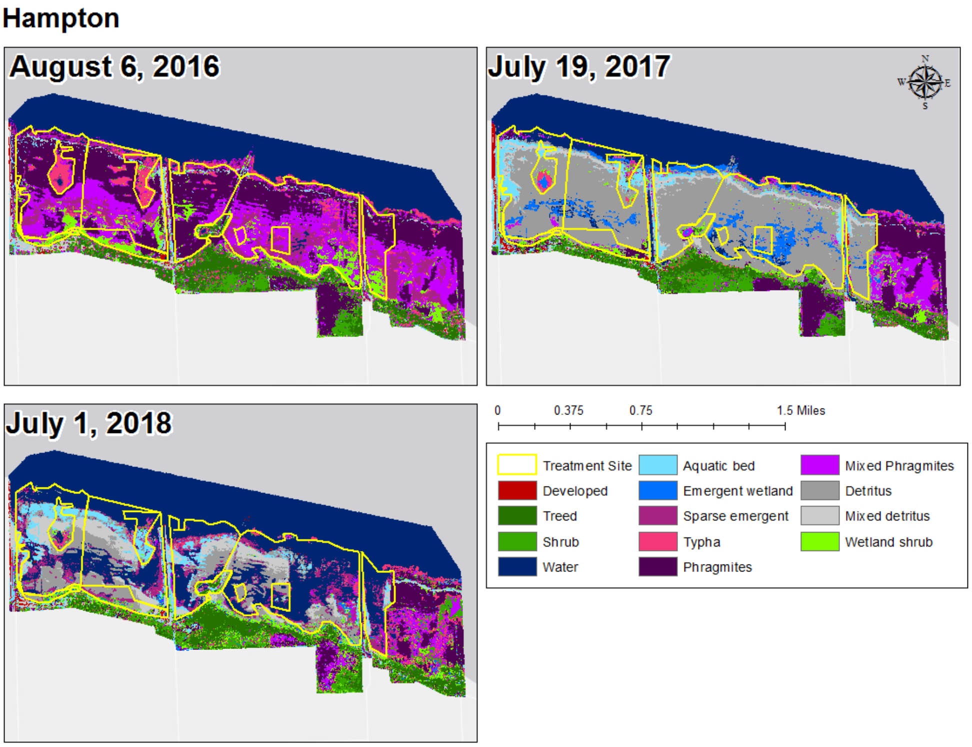

Figure 5: Maps of Hampton area in Saginaw Bay pre-treatment (top left from August 2016), 1 year post-treatment (July 2017) and 2 years post-treatment (July 2018) after a large part of the area was mowed in the winter of 2018.

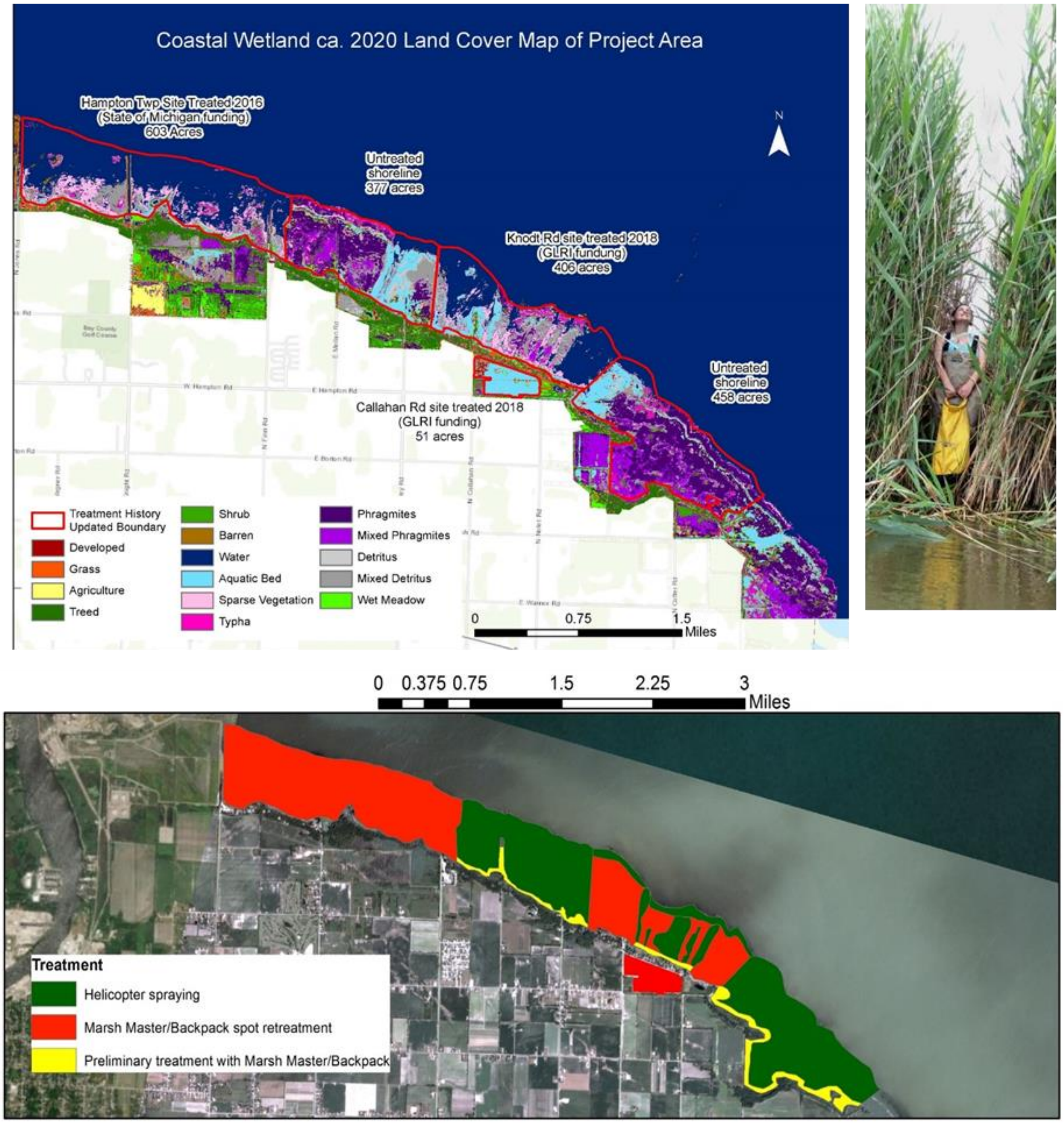

Figure 6. Wetland ecotype map of coastal Saginaw Bay based on Worldview-2 summer 2020 imagery (top) and the treatment plan based on that map (bottom).

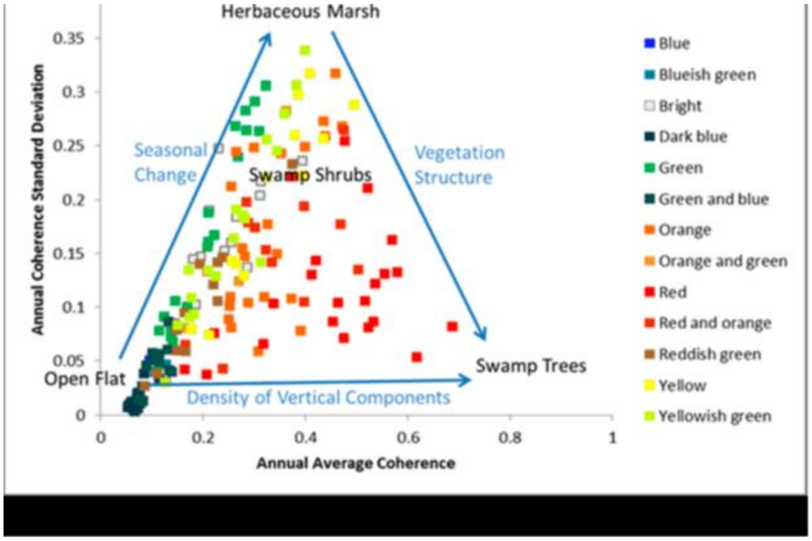

Figure 7: Standard deviation of annual coherence versus average annual coherence of the wetland polygons in the Lake Clear study site. From Brisco et al, 2017.

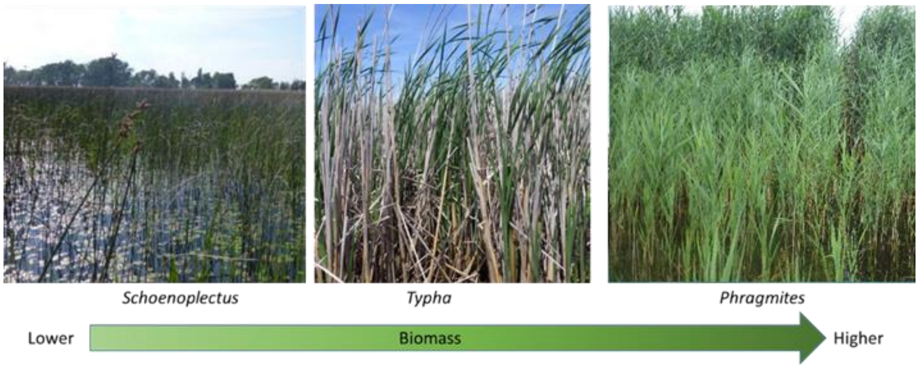

Figure 8: Three dominant emergent wetlands with increasing stem density, height and biomass (Schoenoplectus spp., Typha spp. and Phragmites australis – invasive variety).

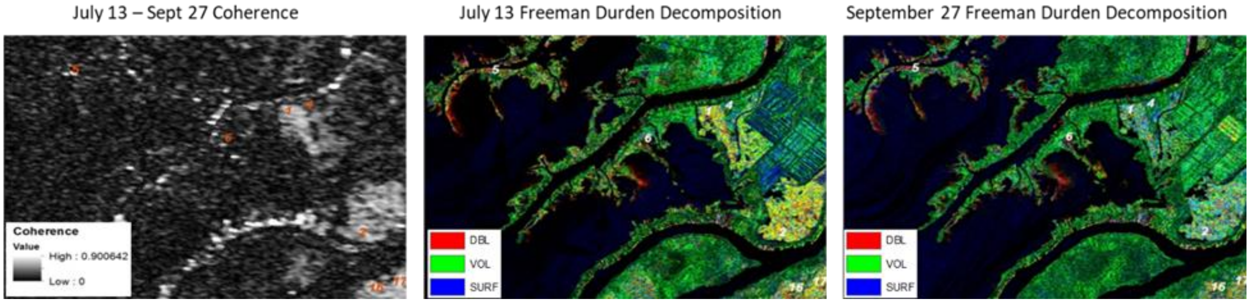

Figure 9: July 13-September 27 2013 Radarsat-2 InSAR pair coherence (left), July 13 (center) and September 27 (right) Freeman Durden (double bounce, volume scatter and surface bounce) decompositions. #1 and 2 are Typha dominated and #5 is Schoenoplectus dominated.

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[i] https://senate.universityofcalifornia.edu/_files/inmemoriam/html/robertcolwell.htm

[ii] https://www.nasa.gov/audience/forstudents/postsecondary/features/F_What_is_Remote_Sensing_prt.htm

[iii] Personal Communication Dr. Murray Strome, November 27, 2021. Dr. Strome, an early Director at CCRS, told the author that they acquired airborne thermal data over Lake Ontario and the wakes of boats were obvious. However, identification of boat wakes was considered a military application of the data and showing such an application was forbidden. To get over this issue, black tape was put over the wakes before the imagery was re-printed and released to those studying the water. (See Slaney et al, 1967)

[iv] When Ryerson was working on his PhD Comprehensive Exam in 1971/72 fewer than 2000 papers had been published in remote sensing related to vegetation, land use and land cover.

[v] Much of the material on Wisconsin was provided by Dr. Jonathan Chipman, now at Dartmouth College.

[vi] The material on the North American Landscape Characterization (NALC) program was provided by Dr. Bert Guindon, a CCRS Scientist who led the program at the time.

[vii] The material in this section is adapted from USFWS report Cooperative Agreement # F18AC0039.