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Wetlands as Climate Mitigation Infrastructure: A Carbon Footprint Assessment of the Wetlands of Kanton Zürich

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Abstract

The destruction of wetland areas has contributed significantly to cumulative greenhouse gas emissions, particularly resulting from the destruction of wetlands with tropical and temperate wetlands. When these areas are restored, the level of emissions can be reduced, eliminated or even potentially become a sink for carbon. As such, there is a potential to restore degraded wetlands to serve as infrastructure for climate change mitigation. This thesis uses the wetlands of Kanton Zürich in northeastern Switzerland, where 96% of wetlands have been degraded over the last century, as a case study to demonstrate the potential for greenhouse gas reduction. Using the Intergovernmental Panel on Climate Change's guidelines, carbon footprint of wetlands is calculated considering the wide range of uncertainty within emissions factors. Through this method, hotspots in emissions are identified, then restoration scenarios are quantified and identified in spatial terms. As a result, this thesis sheds additional light on the state of wetlands within Zürich, and provides a practical method for prioritizing restoration activities based on climate change mitigation.

Introduction

Global Context

Climate change adaptation and mitigation are becoming much more than simply buzzwords; in recent years, global leaders have emerged with a call for action on both fronts. In terms of climate change adaptation, or actions to minimize the local impacts of climate change, there is widespread agreement on the need for action. The European Commission adopted an adaptation strategy to be considered throughout the its policies; the US Federal Government mandated climate adaptation plans for more than 20 federal agencies; and the United Nations Rio+20 published a call for action within their guiding document, *The Future We Want* (European Commission, 2013; Executive Office of the President, 2013; United Nations Development Programme, 2012). Climate change mitigation may be viewed as a more global cause, comprised of actions that reduce emissions with a goal of slowing climate change, which are implemented through policies strengths, innovative technologies, and simple yet effective measures like tree plantings. All of these movements point to a critical juncture where we are required to act. As distinctively spoken by Malcolm X, "the future belongs to those who prepare for it today," indeed, how urban and rural areas plan for climate change adaptation will define the level of resilience over time economically, socially and environmentally.

While the impacts of climate change may still seem distant in some regions, in other areas, the pressures are becoming quite real. The International Panel of Climate Change (IPCC) predicts a high likelihood of climate change related extreme events that will likely increase with additional warming (IPCC, 2014b). For example, unusually severe drought and flood events are affecting areas across the globe, from the US State of California to the Horn of Africa and Southeast Asia. Rising populations, particularly in urban centers, have made vast populations vulnerable to cyclical environmental changes that put livelihoods, health and shelter at risk. It is such situations that can lead to conflicts; in fact, the United Nations Environmental Programme has suggested that 40 percent of events? in the last 60 years have a tie to natural resources, and the United Nations Peacekeeping organization considers climate change as a "threat multiplier" in regions with weak infrastructure or high levels of poverty (United Nations Environmental Programme, 2009).

The Role of Natural Infrastructure

As populations grow worldwide, it follows that there will be a growth in the development of infrastructure necessary to support it. Infrastructure is typically considered a long-lived investment that contributes to the economic or social security of society, and includes structures like roads, bridges and water systems (Moteff, Copeland, & Fischer, 2003). Approximately $3.2 trillion USD will be spent globally on transportation, electricity and sanitation infrastructure in 2013, with an estimated $57 trillion USD investment needed by 2030 to accommodate growing populations (Dobbs, 2013). Climate change is increasingly becoming a factor in decision-making in terms of the size the type, size and scope of infrastructure, both on large and small scales (Hallegatte, 2009). Examples of infrastructure used in climate change adaptation and mitigation are shown in Figure 1 (Mortimer, 2009).

Due to the wide variability in the scope and severity of impact, as well as the variable uncertainty of predictions, infrastructure needed for climate change adaptation and mitigation will likely be a localized affair. Areas with predicted increases in precipitation may require different infrastructure from those with a predicted decrease, and the plan to address these changes must be based on the existing infrastructures in the region, both in terms of the on-the-ground infrastructure and the local and federal policies. Climate change mitigation, on the other hand, contributes to a global mission to reduce emissions and thus required infrastructure may be less directly related to local conditions, though could also support both adaptation and mitigation.

Natural areas are increasingly being recognized for their ability to act as "green infrastructure," providing functions similar to traditional built infrastructure while also supplying a range of ecological, economical and social benefits. Green infrastructure can support climate change adaptation and mitigation in a number of different, and valuable, ways. Switzerland's green

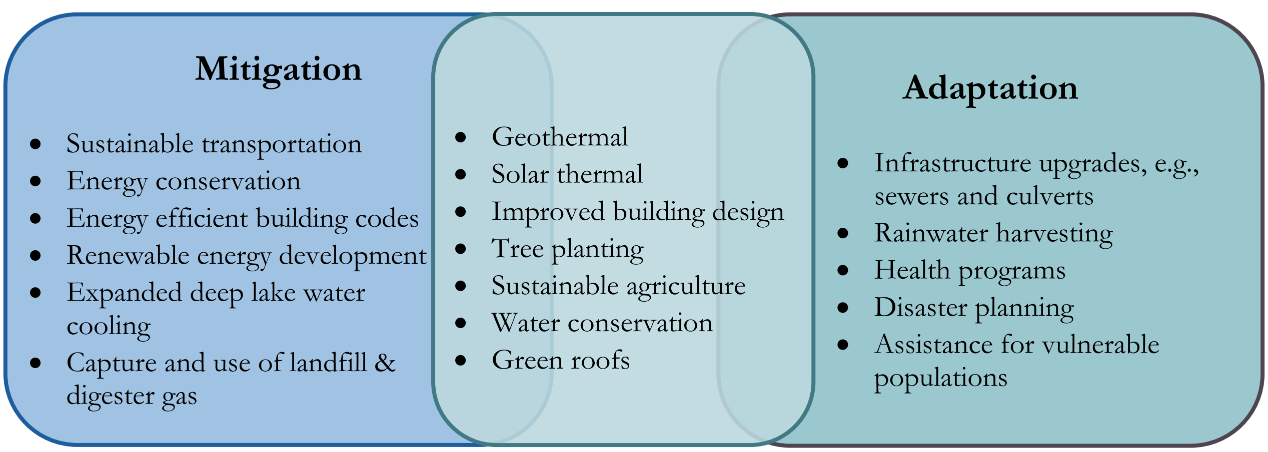

Figure 1 Examples of climate change adaptation and mitigation infrastructure, adapted from Mortimer et al.

infrastructure was valued at CHF 320 billion in 2012, based on its cost of replacement (Swiss Federal Office for the Environment, 2012). Roughly 56% of Swiss green infrastructure is privately owned, thus the burden of its maintenance and protection lies in a grey area of public-private responsibilities. The most valuable segments of the infrastructure are wastewater treatment, drinking water protection, and flood control, values that can, at least in part, be provided by natural areas, such as wetlands.

Wetlands as Infrastructure

Wetlands continue to gain attention for their role in mitigating impacts related to climate change (Arkema et al., 2013; Fountain, 2013; Hanscom, 2013). Commonly found throughout the world, wetlands take myriad forms, from riparian areas to coral reefs to peatlands and beyond. Wetlands as an ecosystem are united by three main factors: hydric soil, hydrophilic plants, and hydrology (Ramsar Convention Secretariat, 2013). Their unique characteristics make them hotspots for biodiversity, nurseries for young animals, and in urban areas, often one of the last refuges for wildlife. However, it is the wetland's fertile soils that have made them prime locations for agriculture and their often prime waterfront location that has made them victim to commercial development.

Worldwide, over 87 percent of wetlands have been lost, with high rates of loss still ongoing, particularly in coastal regions of Asia (Davidson, 2014). While the rate of loss has slowed in recent times, Europe and North American have experienced the greatest long-term loss, with the largest losses occurring between 1900-1950 due to conversion to agriculture (Davidson, 2014; Gimmi, Lachat, & Bürgi, 2011). That said, the areas that remain are often vital parts of communities, whether recognized or not, as demonstrated in the case studies below.

Nutrient Reduction

Cambodia, with only a few operational wastewater treatment plants, relies prominently on wetlands as its primary form of wastewater treatment (Prak, Koch, & Chea, 2013). Its largest city, Phnom Penh, depends on wetlands in the south and southeastern parts of the city for wastewater treatment. Untreated urban wastewater and sewage lines are directed to these open wetlands, where approximately 234 tons of feces, 2,335 m^3 of urine, and 8,154 m^3 of gray water passively filter through the wetland each day before entering the Bassac River (Sokha, 2008; World Bank Water and Sanitation Program - East Asia and the Pacific, 2008). While the value of Phnom Phen's wetlands is not known, a similar situation in Colombo, Sri Lanka, where wetlands are similarly crucial for wastewater treatment, values their contribution of one of their prime wetlands areas as $2.2 million per year for its contribution to household and industrial wastewater treatment alone (International Union for the Conservation of Nature, 2003).

One potentially serious side effect of climate change, according to the IPCC, is algae blooms (IPCC, 2014b). Increased temperatures, which, coupled with changes in precipitation and these large influxes of nutrients, can lead to algal growth in suffocating numbers, exacerbated by disturbances like drought, storms and floods (Paerl & Huisman, 2009). The natural capacity of wetlands to take up nutrients like nitrogen and phosphorus creates a fairly effective, low cost treatment method for these cities. However with little or no monitoring of the resulting water quality, it is unknown how consistent the quality of treatment by wetlands is and how it will react to additional pressures of population growth, industrial wastewater, as well as climate change or additional wetland loss.

Water Temperature Reduction

Increases in air temperature are a common predicted climate change impact. Less discussed, perhaps, are the subsequent increases in water temperature that can occur in conjunction with increased air temperatures (Adrian et al., 2009). In some areas, high temperatures are already considered a pollutant, and thus can be considered as a study for potential future increases in water temperatures elsewhere. In the case of the U.S. State of Oregon, temperature is considered a regulated pollutant in several of its largest river systems due to its impact on endangered salmon species (State of Oregon Department of Water Quality, 2007). Young salmon are especially vulnerable to even small changes in temperature.

The State of Oregon recognizes the ability of wetlands adjacent to waterbodies, like rivers, streams and lakes, to reduce the temperature of water. The mechanism is simple: trees and shrubs create shade that allows the water to cool. Over a large area, the cooling from this shade can significantly decrease the temperature of water. This process was harnessed by the southern Oregon city of Medford, who needed to cool discharge water from wastewater treatment to meet state pollution standards. The city opted to forgo the norm, a commercial refrigeration/chiller system, in favor of an innovative program to restore or protect forested riparian areas along 65km of the city's streams and rivers in order to meet the equivalent temperature reduction requirements of the chiller (State of Oregon Department of Water Quality, 2011). Beyond the temperature reduction, the restored wetland areas have additional ecological and socio-economic benefits for the community, as well as a lower carbon footprint, then the chiller option.

Flood Abatement

Perhaps the most celebrated function of wetlands is their ability to minimize flooding. Wetland soils, especially those with high peat content, can have a sponge-like quality, absorbing rain or floodwater before it enters rivers or bays (Ramsar Convention Secretariat, n.d.). Wetland vegetation can also slow floodwaters as they move downstream, potentially reducing damage. Further, intact stream or oceanside wetlands shield the banks from erosion, minimizing soil loss and protecting property. However, development along coastlines and riverfronts often destroys or damages wetlands.

In Thailand, the farmed wetlands surrounding the city of Ayutthaya, Thailand, are being used to take flooding pressure off Bangkok, which lies roughly 80 kilometers south and is subject to seasonal floods of sometimes epic proportions. For example, in 2011, the Chao Praya River flooded, shutting down parts of Bangkok for months, causing $47 billion in damages (Nikomborirak & Ruenthip, 2013). Nearly all of the Chao Praya river's riparian wetlands have been converted to agricultural or residential areas, leaving very few of the original wetlands intact (IUCN, 1991). However, working wetlands, like rice paddies, retain many of the beneficial aspects of wetlands, including the ability to control floods. The Thai National Water Resources and Flood Policy Committee has implemented a project where, during flood events, Ayutthaya rice paddies can be temporarily repurposed as outlets for excess floodwaters bound for Bangkok (Bangkok Metropolitan Administration, Green Leaf Foundation, & United Nations Environmental Programme, 2009). Known as "monkey cheeks," these flood storage areas trap and hold water until the river's depth subsides and it can be safely released. While the project has been effective, the choice of which fields are flooded and which remain dry is a political issue which has resulted in protests from the farming community (Boonyabancha & Archer, 2011).

Greenhouse Gas Mitigation

Greenhouse gas (GHG) emissions continue to rise to unprecedented levels; in fact, between 2000 and 2010, the rate of increase in emissions rose more quickly than the three previous decades (IPCC, 2013a). The role of wetlands in GHG mitigation is two-sided though, as some wetlands can act as a sink for GHG emissions, making them an asset for GHG reduction efforts, while other wetlands can contribute to emissions, sometimes at a very large scale. In fact, wetlands are the largest global source of methane (Turetsky et al., 2014). The most prominent example of wetlands acting as a GHG source is the tropical peatlands of Indonesia (Chokkalingam, 2004). Widespread conversion to agriculture has been so intensive over the last decades that Indonesia's peatlands, in 2005 alone, emitted over 850 million tons of carbon dioxide – making the country one of the top three global greenhouse emitters (Chokkalingam, 2004).

Indonesia's example may be alarming, but the fact is that this story has played out many times in history. For example, nearly 95 percent of the area or Switzerland's original peatlands were removed, largely for agriculture (Gimmi et al., 2011). Adding to this, rising temperatures in Europe threaten to dry out the remaining wetlands, spurring additional GHG emissions (Middleton, 2012; Wetlands International, n.d.). However, there is an opportunity to restore peatlands as a mechanism for climate change mitigation. Many existing wetland areas have artificial drainage structures, which could be simply removed in order to rewet organic soil, thus slowing or stopping additional emissions, and potentially becoming a sink of GHGs, towards a global benefit (IPCC, 2013b). If trees and shrubs are included in the revegetation plan for a restored wetland, the net carbon sequestration is even higher.

However, wetland conservation and climate change mitigation must strike a balance in order to meet the needs of both the environment and the community. Wetlands used in agricultural operations provide an important livelihood for many people around the world, and their reflooding interrupts the ability to profit off this land. Ecosystem services, or the benefits the natural system provides to society, have become the de facto metric for understanding this balance. The next section will discuss how ecosystem services are used for wetland valuation and the downsides such an approach may face.

The Promise, and Pitfalls, of Ecosystem Services

As populations swell and communities grow, shifting the perception of federal and local government agencies to consider wetlands as valuable infrastructure in development and master planning can help to deliver cost effective and multifunctional solution for climate change resilience. However, in some areas, a disconnect remains between the values of a wetland as a functioning entity in and of itself and the land's value for other worthwhile, and arguably very necessary, pursuits like homes or food. If the true value of a wetland was quantified, removing a saltmarsh to build a new waterfront complex in an area known for hurricanes, for example, could represent a form of market failure if the value provided by wetlands is greater than the value of the new development.

Russi et al (2013) list the various functions of wetlands that have the potential to lessen climate change impacts for society, related to the framework of ecosystem services as defined by the Common International Classification of Ecosystem Services (CICES) (European Environmental Agency, 2013). Defining a value for these services provides a platform on which natural areas can compete in market-based systems, such as real estate. However, these functions and services are not always clearly recognized or properly valued (Gedan, Kirwan, Wolanski, Barbier, & Silliman, 2011; Nuwer, 2013). For example, managers of wetlands identified as internationally important under the Ramsar Convention on Wetlands often underestimated the ecological and social values of wetlands, demonstrating that, even those who are arguably the most aware of wetland ecosystems, might not fully recognize the presence or absence of critical or valuable services (McInnes, 2013).

Table 1 Examples of climate change impacts, wetland functions that could assist with their adaptation and mitigation and the corresponding ecosystem services

Wetland Function(s)	Climate Change Impact	Ecosystem Service
Groundwater storage and replenishment	Change in rainfall timing and amount	Provisioning service: freshwater
Shoreline stabilization Storm surge abatement	Increased intensity in coastal storms	Regulating service: water regulation
Pollution uptake and burial	Decreased access to clean water	Regulating service: water purification
Riparian vegetation shades water to reduce water temperature	Increased surface water temperature	Regulating service: climate regulation
Nutrient uptake by plants	Increase in algae blooms	Regulating service: water purification
Water temperature reduction		Regulating service: climate regulation
Carbon sequestration by plants Carbon sequestration by soil	Excess GHG	Regulating service: climate regulation

Developing a method for such an assessment that is, on one hand, accurate, equitable, and transparent and, on the other hand, doable without a major investment of resources, has remained a challenge. Richard Norgaard expands these arguments further, saying that ecosystem services, once adopted as a convenient construct for valuation, has now become a de facto measurement, to the detriment of our natural systems (Norgaard, 2010). He argues that ecosystem service valuation has thus far only been successfully conducted on a site-by-site basis, yet organizations continue to accept the framework on a national and international setting. Furthermore, Norgaard demonstrates that ecosystem service valuation can reduce complex systems to rather simple economic terms, which depend on the ever-fickle values of society.

Wetland areas, in fact, demonstrate that idea well. In the past, wetlands were regarded as wastelands with little value in their present form. For example, Conrad Escher, a renowned Swiss scientist, engineered a project in the early 1900s to straighten the Linth River, removing its connection to riparian wetlands, in order to reduce problematic flooding as well as the risk of Malaria (Greene, 2014). The project also opened up additional lands for farming, benefitting the local community. Today, flooding continues to be an issue on the river, and the project is being partially reversed, this time using wetlands as flood control. The same story is true in many other regions – as values change and science and engineering evolve, many wetlands are being restored where they were once eradicated.

Whether or not ecosystem services are a perfect model, there is still a need for a system with which to understand and compare natural systems, particularly in the case of master planning. The Intergovernmental Platform on Biodiversity and Ecosystem Service (IPBES) points to the need for decision makers to be able to process complex scientific information, arguing that ecosystem services provide a platform for spatial and temporal assessment of ecosystem function (Perrings et al., 2010). However, IPBES acknowledges weakness in this approach that could lead to a false signal in decision-making, such as a lack of understanding about interactions between species and human activities, uncertainty in environmental conditions, and a lack of inclusion of functional diversity.

Thus, there is still a need to improve upon the way the landscape is evaluated through a decision-makers lens. Ecosystem service evaluations can be challenging; technically, evaluations can be time-consuming and resource intensive to conduct, especially difficult in areas with limited scientific capacity (Booth et al., 2012). Further, the data can be difficult to interpret in a transparent fashion to scientists and non-scientists, and uncertainty is often unreported or under-described. The Ramsar Convention on Wetlands, who have not formally adopted the term ecosystem services (Stroud, 2012), still sees a need for a rapid assessment technique to understand the societally relevant benefits of wetlands that is designed for rapid adoption (N. Davidson, personal communication, 11 September, 2013).

Problem Statement

It is with this scenario – wetland loss, climate change adaptation, and ecosystem service assessment challenges – under which this thesis strives to add value. This thesis has two primary aims, demonstrated through a case study on the wetlands of Kanton of Zürich in northeastern Switzerland. Firstly, this thesis contributes to the body of literature on the degree to which wetland areas can be considered as infrastructure for climate change mitigation, looking specifically at their potential to sequester carbon following wetland restoration. Secondly, this research aims to contribute a methodology for wetland ecosystem service assessment that could contribute to more rapid ecosystem valuation to inform decision-making. This is accomplished through a reliance on existing data, and including uncertainty within the results allows for a broad understanding of the wider trends within the data as well as points to the usefulness of such a methodology. To further the potential for adoption, methods were employed that could be scaled to larger areas or transferred to different geographical regions. Figure 2 visually demonstrates the themes within the thesis.

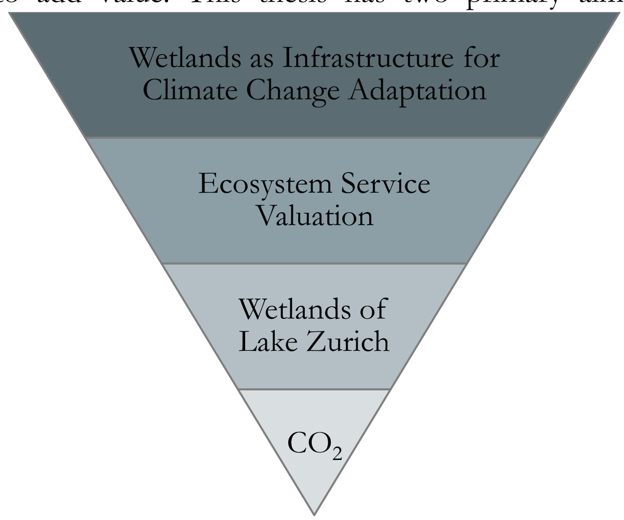

Figure 2 Overall structure of this Masters thesis

This thesis applies the methodology to the setting of the wetlands of the Kanton of Zürich in northeastern Switzerland. This report looks solely at the carbon sequestration potential of wetlands, referred to throughout this document as the "carbon footprint." Focusing on wetlands that have been altered over time, the impact of the widespread drainage of wetlands is considered and quantified. This is particularly relevant in light of the IPCC's warning that climate change could bring additional drying to wetland ecosystems, increasing carbon emissions from drying organic soils (IPCC, 2014c). Through the lens of carbon emissions, suggestions can be made to prioritize specific wetlands areas for restoration, potentially adding a market mechanism for ecosystem restoration using carbon markets. Carbon is used here as a representative value, however additional ecosystem services can, and should, be added in order to understand these areas for their multiple values. The following section summarizes the motivation behind carbon footprinting, then goes on to describe the study site in more detail.

The Trouble with Wetlands & Carbon

While forests have long been the darling of land-based carbon offsets, there is a growing pressure to include wetlands as a viable source of carbon sequestration within REDD+ and the Green Climate Fund (Alexander et al., 2011; Friess, 2013; Lattanzio, 2012; United Nations Environmental Programme, 2008). With millions in funding potentially on the table for emissions reductions projects, there is a high interest in including the restoration and conservation of valuable and highly threatened wetlands into these programs. However, to include wetlands as a sink of carbon, the amount to which they provide this service must be quantified. This is also relevant for signatories of the Kyoto Protocol, who must report GHG emissions related to land use change, for both forest and wetland areas (Secretariat for the United Nations Framework Convention on Climate Change, 1998). However, the degree to which wetlands contribute to the global GHG balance is still a matter of debate.

Some wetlands, particularly those with organic soil, capture and store large pools or carbon, while others emit large amounts of methane, contributing to the Earth's carbon balance (Donato et al., 2011; Mitra, Wassmann, & Vlek, 2005; Turetsky et al., 2014). The amount of carbon sequestered or emitted is highly related to human activities, such as forestry, drainage and aquaculture, and varies based on the conditions on each individual site (IPCC, 2014a). As such, it has been difficult to quantify the exact flux of GHGs related to wetlands, and is still a matter of research and debate. For example, in 2013, Mitsch et al found that wetlands are a net global sink for GHGs over time even considering methane emissions, finding that short-term fluxes in methane are outweighed by carbon sequestration over time spans of roughly three centuries (Mitsch et al., 2013). Neubauer examined the same dataset, but found that the time span over which wetlands become global sinks could be up to 14,000 years, especially freshwater wetlands in temperate climates (Neubauer, 2014). He also re-ran Mitsch's model with the inclusion of lesser-studied N_2O, which served to lengthen the time to reach this emission balance. Bridgham et al added further to the critique by pointing out an error in the estimation of methane reduction over time as well as the carbon emissions, and the small number of sites used to create estimates of emissions.

The debate around Mitsch et al points to the key issues potentially preventing wetlands from becoming the new stars of carbon sequestration. First and foremost, there is limited information as to what degree wetlands can sequester carbon dioxide, and even less information on methane and other GHGs. Most studies are based on a limited number of sites that have been studied for a short period of time. Therefore, all numbers should be considered with careful attention to the conditions of the survey, the techniques employed, and the consideration of uncertainty. Furthermore, how these numbers are calculated is critical – which GHGs are included, what time spans are used, and so on – affect the answer greatly in often technical ways, causing understandable confusion for governance bodies tasked with regulating emissions and funding emissions reduction projects.

IPCC & Switzerland Provide Guidance

The IPCC has attempted to add clarity to the debate by publishing two guideline documents on wetland emissions due to human actions, focusing mainly on the impact of land use change consistent with Kyoto Protocol requirements and in sync with offsetting programs. In 2006, guidelines were released to help refine the emissions data for wetlands, focusing on one of the most pressing issues at the time, and today, the conversion of peatlands for agriculture or peat extraction (IPCC, 2006). The 2006 guide also offered information on the GHG contribution of wetlands used in rice cultivation, a widespread use of wetlands and also one of the most widely studied crop types.

The guidelines were met with criticism for what they included, and what they left out. For example, the NGO Wetlands International pointed out that the guidelines included climate zones that were not defined clearly and suggested default emissions factor values that are either too high or low, according to research not included within the guidelines (Wetlands International, 2009). Further, the guidelines left out the majority of wetland types. In 2013, additional guidelines were released as a supplement to the 2006 Guidelines in order to provide a broader look at the impact of anthropogenic impacts on different wetland types (IPCC, 2014a). The document also focused only on land use change scenarios, such as draining or rewetting wetlands, but expands to a broader range of wetland types and climates, such as coastal wetlands. The IPCC provides a methodology based on common conventions for different wetland types, varying by land use and soil types.

As a Kyoto signatory, Switzerland followed this direction and developed its own set of emissions factors for a limited set of wetland types: peatlands that have been drained for agriculture or other reasons (Agroscope, 2011a). The emissions factors are based on three studies on three drained bogs in Switzerland, again representing a limited number of sites and including high uncertainty, though the sites are in the same general geographic area, which reduces some of the uncertainty. Switzerland also offers guidance on quantifying emissions from forested bogs that have been drained, adopting the 2003 IPCC estimate for temperate forests. This emission factor is one number, without uncertainty, valid for any type of forest on any type of land in the temperate region (IPCC, 2003). These numbers have been adopted by the government of Switzerland for Kyoto Protocol reporting, and were also considered within this thesis.

While IPCC and Swiss numbers are used in this thesis, they only offer guidance on a limited set of wetland types, thus to calculate a carbon footprint of a range of wetland types, such as with this study, additional sources must be used. As such, additional emissions factors were included in this study to meet the variable types of wetlands in the study area. Also, due to the uncertainty within emissions factors, other relevant emissions factors were included for reference. The choice of emissions factors is further described in more detail in the methods section.

Case Study Site: Kanton Zürich

The Kanton of Zürich covers 1,729 km^2, located in the lowlands of northeastern Switzerland in central Europe. Following the last ice age, retreating glaciers left behind vast wetland areas as peat filled in glacial moraines and drumlin fields. Using old maps, Gimmi et al found that wetlands covered 137.6 km^2 of the Kanton, or 8% of total land area, in 1850 (Gimmi et al., 2011). This number has since decreased dramatically; by 2000, 96% of these wetlands had been destroyed, covering only 1% of the Kanton's total area. The total area of wetlands was reduced, and so was the size of individual wetlands. Individual wetland size decreased from an average of 3.2 hectares in 1850 to 1.7 hectares, pointing to increasing fragmentation of wetland habitats.

The most significant period of wetland loss since 1850 was between 1900 and 1950, during which large swaths of land were converted to agriculture to feed a continent largely at war. High demand for food led to the development of more efficient drainage techniques (Moser, Prentice, & Frazier, 1996). The changes in Switzerland are consistent with trends throughout Europe, where conversion to agriculture dramatically changed the landscape (Davidson, 2014). Large infrastructure projects, such as the construction of the Kloten airport, as well as peat mining contributed to the destruction.

Wetland destruction in Switzerland began to gain importance in the 1970s. In the late 1970s, Switzerland approved two international wetland protection acts, the Ramsar Convention on Wetlands (The Swiss Federal Council, 1976), followed by the European Convention on the

Conservation of European Wildlife and Natural Habitats (Council of Europe, 1979), both pledging to protect and restore wetland ecosystems. Domestic policies came later, with the passage of policies to protect water and migratory bird habitats and raised peatlands (*hochmoore*) of national importance in 1991 (The Swiss Federal Council, 1991a, 1991b). Fens (*flachmoore*) were protected in 1994 (The Swiss Federal Council, n.d.), followed by a more general wetland protection bill, protecting moors of special beauty or national importance in 1996 (The Swiss Federal Council, 1996). This has led to the protection of 3300 hectares of wetland areas in Kanton Zürich.

The drainage of wetlands, particularly those with organic soils, can release large amounts of GHGs into the atmosphere. Soil with high organic content can oxidize when dried, releasing CO_2 and N_2O (IPCC, 2014a). The draining, conversion and fragmentation of wetlands is similar throughout many areas in Europe and North America. Furthermore, the types of wetlands in the study area are common throughout the temperate regions. In this sense, the methodology has the potential to be easily transferable to other regions. This thesis considers both the past and present wetland sites in Kanton Zürich, using 1900 as the baseline. Because the majority of wetlands were impacted in the first half of the 20^{th} century, this time period encompasses the majority of present and past wetland sites. The following section explains how the IPCC method for carbon sequestration potential was applied to the wetlands of Kanton Zürich.

Methodology

This study involved four major steps. Firstly, wetland areas were identified. Next the sites were characterized by the three factors needed to understand carbon footprint, land use, soil type and hydrology, and each site's protection status was noted. Finally, emissions factors for each type of wetland were identified, then applied. Finally, a scenario analysis was conducted to estimate the impact of restoration on GHG emissions.

Wetland site identification

This thesis was conducted in two phases, allowing the author to test the potential of the method to be expanded to broader geographic scales, as shown in Figure 3. The first phase involved a trial of the method on a smaller area, which was then expanded to include the entire Kanton Zürich. The details of each step are included below.

Phase One

The first step involved the wetlands around a specific set of geographic features that encompass the largest remaining protected wetlands areas in the Kanton Zürich. This includes Lake Zürich, the Sihl River valley, Pfäffikersee, Lutzelsee, and the moorland areas of Neeracher Reid, Maschewander Allmen, Frauenwinkel, Wetzikon, Hinwil and Wirzel. The study area was determined to be the watersheds surrounding those wetland areas in order to understand the area immediately surrounding the wetlands.

The watersheds were defined based on the classifications developed by the Swiss Federal Office for the Environment (FOEN), defining watersheds on different scales, from large-scale basins to small-scale sub-basins (Swiss Federal Office for the Environment, n.d.). Each sub-basin is assigned a unique code, and is also associated spatially to all watersheds that drain into that sub-basin. In ArcGIS 10.1, the codes are labelled as "H1" (the lowest watershed code that enters the target sub-basin) and "H2" (the highest code that enters the sub-basin). For each watershed and wetland area, the H1 and H2 codes were calculated for all watersheds entering the target area. Using the Select by Attribute tool, the select parameters were defined as

$$H1_{Area\ 1} \geq X\ and\ H2_{Area\ 1} \leq X\ or\ H1_{Area\ 2} \geq X\ and\ H2_{Area\ 2} \leq X\ or\ \ldots$$

for each sub-basin found to be entering the target area. This process was completed for each target area, then the watersheds were merged to form the study area. The total watershed was then clipped using the CLIP tool to the borders of Kanton Zürich.

Wetland areas present in 2000, as identified by the Gimmi study, were used as the study sites. In order to preserve the areas defined as protected areas, which in some case differ from the Gimmi wetland map, the outline defined by FOEN was used as the boundary (Bundesamts für Umwelt, 2007a, 2007b). The Gimmi wetlands were combined with FOEN protected areas using the COMBINE function with WSL as the "dominant" type. Thus if a protected wetland area falls within Gimmi wetland, it was combined with the Water, Snow and Landscape (WSL) wetland type. Through this method, 364 individual wetlands were identified as the study area for Phase One. The subsequent steps of the classification and analysis were conducted on Phase One wetlands.

Phase Two

Phase Two of the project considered a larger scope of wetlands. In this case, the Gimmi wetland map from 1900 was used and the geographic area was expanded to all of Kanton Zürich. Wetlands shown on the 2000 map were assumed to be still acting as wetlands, which was found to be true in almost all cases. In contrast, the 1900 set of wetlands, some areas remain as wetlands, some have been drained, and others have been converted to new uses. Care was taken to remove any areas from 2000 that overlap with the 1900 wetland map in order to prevent any double counting. This was accomplished by using the ERASE function in ArcGIS to remove areas from 1900 overlapping with 2000 areas, then combining the subsequent dataset with the 1900 wetlands.

Using this broader set of areas allowed for a more broad consideration of land use change scenarios, as well as to expand the number of wetlands under consideration in the report to a more logical geographic area that may be more useful for the conservation practitioner. In Phase Two, the number of wetlands increased by a degree of magnitude to 3121 wetland sites.

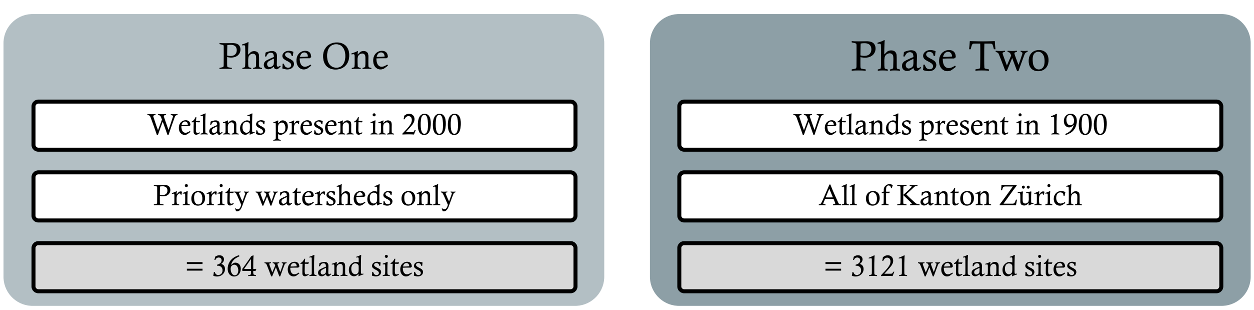

Figure 3 Structure of the two phases of the project

Wetland characteristics

Once the wetland areas were identified, additional characteristics were added within ArcGIS using the SPATIAL JOIN tool. While any number of characteristics could be added to the dataset, those that are relevant to the carbon footprint calculations are included here: land use, soil type and hydrology. These data are commonly collected throughout Europe and North America, and possibly other places, thus increasing the transferability of the methodology.

Land use

Land use is an important factor in carbon footprint calculations. Because many wetlands are repurposed for other uses, such as agriculture, understanding the way in which the land is used is vital for understanding its GHG impact. The IPCC defines land uses in the following categories: forest land, cropland, grassland, wetlands, settlements and other land (IPCC, 2014a). These categories demonstrate the potential changes a wetland can experience over time, all variations of which were found within the Kanton Zürich wetlands.

Land use in Kanton Zürich was determined primarily through the Statistical Land Use Dataset *Arealstatatistik Schwiez* and CORINE land use classification system (Steinmeier, 2013, Bundesamt für Statistik, 1998, 2011). CORINE, or coordination of information on the environment, is a long term data collection project launched by the European Union in the 1980s and presently run by the European Environmental Agency. Due to long-term coordination between Swiss and European Union agencies, the dataset has a similar structure to the Swiss program *Arealstatistik Schwiez*. As such, the Arealstatistik was used as a primary dataset for land cover classification, and CORINE was used as a back up in instances where there was not clarity within Arealstatistik.

Switzerland has conducted detailed land use and change characterization surveys in 1990, 2000, 2006 and 2012. Because the 2012 data have not yet been released, this study uses data gathered in 2006. Data were gathered through high-resolution aerial photo mosaics gathered every three years by SWISSIMAGE (Swisstopo, 2010). The images are high resolution, down to 0.25 – 0.5m in most locations. The data were organized into land use following a hierarchical structure, comprised of three levels with increasing resolution. As such, a land use class was assigned for every parcel of land in Switzerland, which in most cases was at a resolution sufficient to classify land use. In the case of very small wetlands, additional information from aerial photos was used.

A few additional notes on the classification of each land type are provided below:

Wetlands: The wetlands classification was done using several data sources, though primarily relying on CORINE and the Gimmi map. Wetlands present on the 2000 Gimmi map were automatically classified as wetlands. CORINE differentiates wetlands in terms of "inland marshes" and "peat bogs: under the category of "inland wetlands", and "moors and heathlands" under the category of "forest and natural areas." In some cases, the CORINE dataset was not high resolution enough to capture small wetland areas. As such, wetland areas that are protected were de facto added to the wetland category to ensure all areas were captured. On some occasions, it was necessary to review Swisstopo aerial photos in order to confirm the existence of a wetland.

Croplands: Croplands were classified based on the CORINE group of "agricultural areas." All types of agricultural activities are grouped together, including areas used as pasture. Under the IPCC classification system, agricultural areas are defined as "managed areas" thus pasture areas, which inherently are modified by grazing animals and use of fodder, are included as croplands.

Grasslands: There were no areas classified as a "natural meadow" within the study area, i.e. areas with a natural grass cover not used for grazing. However, since many croplands were classified as pastures, this study used cropland as the primary land use classification but included grassland as an additional descriptor for those sites. In this way, grassland can still be used as a classifier since it is relevant for restoration and conservation issues, but the proper emissions factor for croplands could be used for the carbon footprint.

Forests: A number of wetlands that have tree cover were included in this study, classified as "forests" under CORINE. Understanding the coverage of trees on a wetland site is important as it changes the sequestration potential of the landscape. However, this study only considered sites as forests if that was the main land use classification. It is possible that some sites names as wetlands have trees on them, but are not included at this scale.

Settlements and Other: A number of wetlands that existed in 1900 have been removed for settlement or other uses, such as roads, buildings or sports fields. Only one wetland from 2000 was classified as a settlement. There are no default emissions factors for settlements, but the 2013 IPCC Guidance suggests using the emissions factor of the land use of the wetland prior to modification. However, these newly found settlements were wetlands before they were converted, and many have been converted for a very long time. Because of the permanent nature of the settlements included in this study, i.e. there is little or no hope for restoration to natural conditions, the author felt that using the emissions factor for a wetland was an inappropriate assumption and had the potential to artificially inflate the carbon emissions calculations. As such, areas classified as settlements were excluded from this study. If there is the potential for restoration of a settlement area, it could easily be added back into the calculation based on historic conditions.

Soil type

The IPCC simply requires that soil be classified as either organic or mineral soil. As such, only a cursory knowledge of soil is required to make such a determination, and even simple soil surveys may provide enough information. For Kanton Zürich, ample soil information was available within the Kanton Zürich Soil Map (*Bodenkarte*) and the Soil Map for Agricultural Areas (*Bodenkartierung der Landwirtschaftsflächen*) (Amt für Raumentwicklung Abteilung Geoinformation Fachstelle, 2013; Eidg. Forschungsanstalt für Agrarökologie und Landbau, 1997). Using these maps alongside the Kanton's map of protected wetland areas, areas meeting at least one of the following characteristics: classified on the Kanton Bodenkarte as having moor or half-moor soils, classified under the Kanton Agriculture Map as a humic soil, classified as a protected moor by the Kanton. The remaining soils were classified as mineral soil. An example of organic and mineral soil types found in a Kanton

Figure 4 Photos displaying examples of organic soil (left) versus mineral soil (right) within the study area (Photos by

author)

Hydrology

All sites were classified as either having altered hydrology or natural hydrology, in simple terms, drained or wet. Altering wetland hydrology is a pervasive tactic for removing excess water from a property and allowing other activities, such as farming, to continue. In terms of carbon emissions, draining particularly organic soils allows soils to dry out, releasing carbon into the atmosphere. As such, recognizing where drainage is present is a key element of this exercise.

There are no straightforward data sources that considered altered hydrology for the entire study area. The Kanton Zürich has a melioration map which specifies areas for which the Kanton has sponsored drainage activities (Amt für Landschaft und Natur, 2012). Beyond that, decisions had to be made for each area, following some general rules. Cropland was generally considered to be altered hydrologically. Forested wetlands were considered to be unaltered, unless the Kanton map specifically denoted otherwise. Based on examinations of aerial photos, it was found that many wetlands have drainage within them, thus could not be explicitly marked as unaltered. Without a mechanism for automating the process, wetland areas were examined using Swisstopo for signs of drainage. Signs of drainage are primarily straight ditches that cut through an area, often leading to a stream or lake; two examples are shown in **Error! Reference source not found.**.

Wetlands were considered as a whole unit, thus if drainage was observed in one area of the wetland, the entire system was classified as altered. Because most wetlands are small in size, ~one hectare, this does not represent a significant error. However, if the study was to be conducted in more detail, it is possible that individual wetlands could be parsed into drained or undrained areas, though this would require a site visit and analysis, requiring time and resources.

This effort represents the most time consuming activity within the classification system, requiring roughly 20 hours of screen time to confirm the presence of drainage in the system. It is possible the effort could be streamlined by training GIS to recognize "straight lines" within wetland areas, especially since they are often visible in regular maps, not only aerial photos. If this could be accomplished, the methodology would have fewer barriers to widespread adoption. That said, the analysis to identify the drainage doesn't require special skills or expertise, thus the only investment is in time.

Figure 5 Examples of wetlands with drainage ditches within the study area (Photos from Swisstopo)

Quality Control

Since many datasets have high resolution, ensuring that land use classification is correct is an important activity to ensure accuracy. To confirm the accuracy of classifications, site visits were made to ~35 sites, where the land use, soil and hydrology were inspected firsthand. Another roughly 500 sites were evaluated based on Swisstopo aerial photos. That said, it was outside of the scope of this project to visit each wetland, thus it is possible that some areas are mischaracterized.

Summary

An overview of the data sources used to classify the wetlands is provided in Figure 6. Two additional characterizations that are relevant for understanding restoration potential were added to the wetlands areas beyond what is necessary for the carbon footprint calculation (P. Weber, personal communication, 3 September 2014). Protection status, based on the Kanton's inventory of protected wetlands, was added in order to understand what the Kanton's involvement is with the land, useful when thinking about restoration scenarios. Land that is protected may be easier to restore. Secondly, whether parcel was a grassland or not was added to each characterization, assuming that grasslands are also more easily restore.

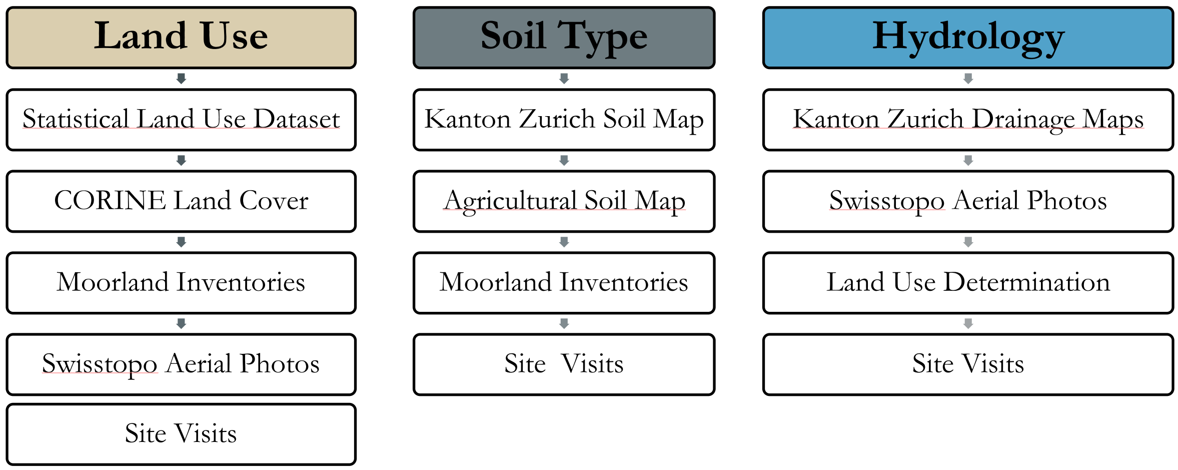

Figure 6 Data used to determine land use, soil type and hydrology determinations.

Emissions factor selection

Once the wetlands were characterized, an emissions factor was assigned that represents each type of wetland. Emissions factor refers to the amount of a greenhouse gas that is emitted or sequestered for a particular unit over a defined time period (IPCC, 2014a). In this study, CO_2 was considered, thus the emissions factors are expressed in terms of tonnes of CO_2 per hectare per year. They are typically determined by on-the-ground measurements of carbon sequestration within wetland soil, with measurements lasting for varying amounts of time (Freibauer, 2003).

There have been many studies aiming to quantify the carbon sequestration rate of wetland soil, leading to a range of different emissions factors. For the practitioner, this can cause difficulty in deciding which emissions factor to select. Further, there have been a far greater number of studies conducted on wetlands with organic soil than mineral soil, thus there are fewer options for sources for the less studied wetlands types. In their 2013 Guidelines, the IPCC aimed to add clarity to its 2006 Guidelines by compiling emissions factors through existing literature sources. This led to a perhaps more comprehensive look at the state of the scientific literature, but also compounded the uncertainty within the emissions factors and a generalization of the results, thus their accuracy in different situations is questionable (Leggett, Pepper, & Swart, n.d.).

To reach a more appropriate number for an area, the IPCC recommends the creation of a localized model, which can be complicated, time-consuming, and resource intensive, but also potentially experiencing the same issues of uncertainty. In the absence of local models, the IPCC numbers may the next best estimate, and are thus considered within this thesis as a mechanism for comparison as well as where local numbers are not available. Switzerland provides guidelines for land use change in Swiss peatlands based on existing studies of Swiss wetland sites (Agroscope, 2011a). To understand the impact of the emissions factor, and its related uncertainty, on carbon emissions calculations, both Swiss and IPCC emissions factors are included in this study.

IPCC and Swiss Guidelines only suggest emissions factors for some types of wetlands, thus to complete a study of wetlands throughout this study area is not possible using these sources alone. Further, the emissions factors compiled by the IPCC and Agroscope do not represent the full range of locally appropriate studies on the topic, only a subset. And, in fact, relying on IPCC or local guidelines is merely a suggestion, thus a practitioner could potentially pick any emissions factor with appropriate justification depending on the purpose of their study.

To gain a broader understanding of emissions factors, a systematic review of additional literature sources specific to wetlands in Switzerland and Europe was conducted. A total of 37 emissions factors were found that fit the geographic parameters of the region, studies or reviews based in either Switzerland or mainland Europe. In the case of wetlands with unaltered mineral soil, no studies were found within the geographic area, thus a study by Bridgham et al from the temperate region of North America was used (Bridgham, Megonigal, Keller, Bliss, & Trettin, 2006). A full accounting of the sources used can be found in Appendix 1.

The range of emissions factors for wetland types in this study area, grouped by land use type, is displayed in Figure 7. The unit of measurement for each factor is metric tons of CO_2 per hectare per year; in some cases the factor had to be converted to this unit. The horizontal lines represent the mean value. Error bars are shown in cases where uncertainty is reported, and left off where no uncertainty is discussed.

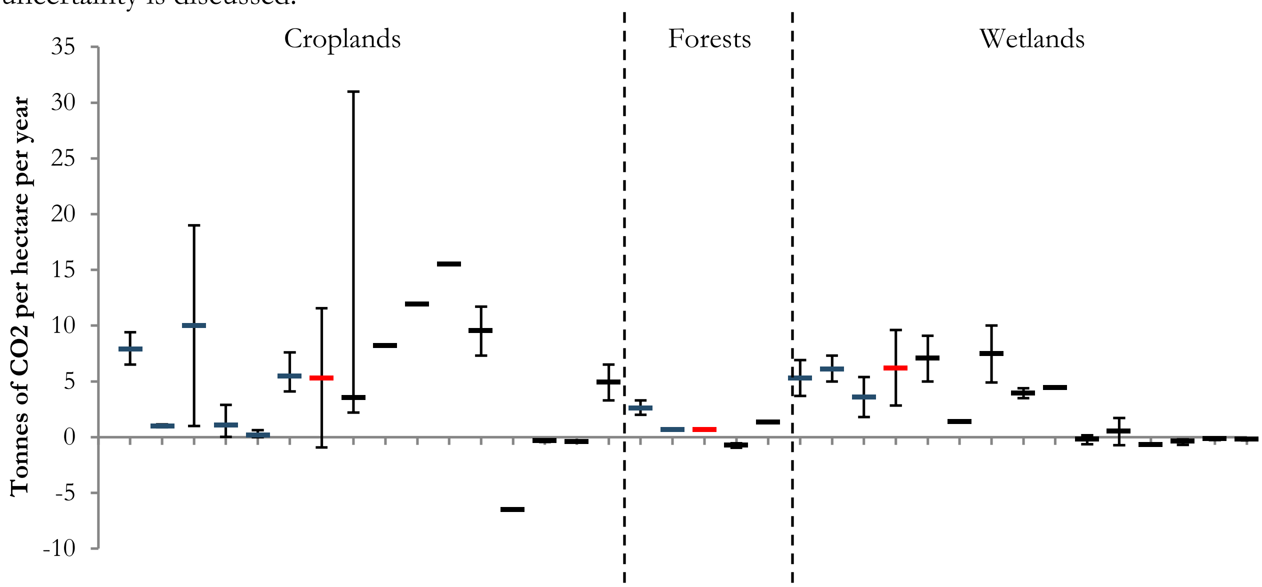

Figure 7 Range of emissions factors, grouped by land use type. Error bars represent the uncertainty reported in the study. If no uncertainty was reported, no error bars are shown. IPCC factors have blue bars; Swiss factors have red bars.

It's clear that the emissions factors can range quite broadly, but also where research interest has been concentrated. The most studies that have been completed related to organic soil, which is logical since they are most often implicated as greenhouse gas emitters. The following section will provide a general discussion about the emissions factors found for organic soil, allowing us to better understand the difference between sources as well as their relative importance in terms of the final results.

Croplands with organic soil

Demonstrated in Figure 8, emissions factors for croplands with organic soil are shown, with the Swiss, IPCC and Freibauer et al numbers highlighted (Agroscope, 2011b; Freibauer, Rounsevell, Smith, & Verhagen, 2004; IPCC, 2006). Each of these studies are essentially review papers, pulling from a range of sources, while the other sources are largely one-off studies of a single site. The IPCC and Freibauer pull from a particularly large set up emissions sources, thus increasing the uncertainty of those numbers. This points to the issue of uncertainty within emissions factors, demonstrating how a value can be highly variable depending on the site and the measurement protocol. However, all sources have a mean near or below 10 tonnes $CO_2ha^{-1}yr^{-1}$ and only one study, based in Switzerland, found these areas to be a carbon sink (Hediger, 2006). The number adopted by Switzerland, however, was found to be positive, thus in sync with all of the other sources considered.

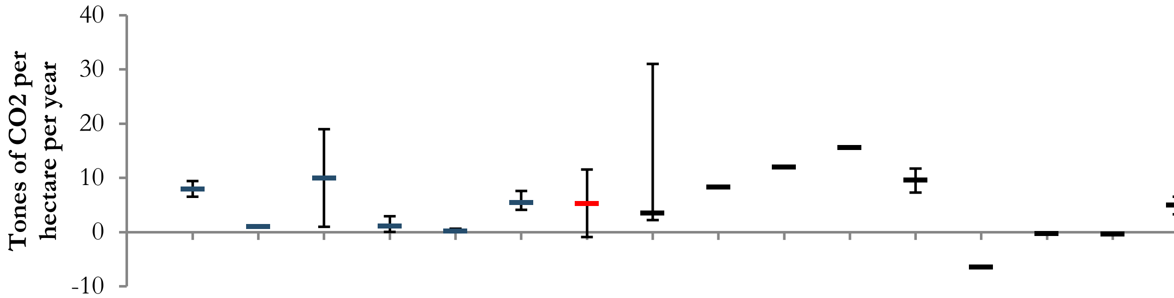

Figure 8 A subset of the emissions factors, showing only croplands with organic soil. IPCC factors have blue bars; the Swiss factor has a red bar.

Wetlands with organic soil

Wetlands with organic soil were the most widely studied habitat in existing literature, as seen in Figure 9, and those with altered hydrology (on the left-hand of the dotted line) had the most research conducted. The IPCC includes four estimates for emissions factors for drained wetlands, depending on their level of nutrient richness. Because nutrient richness was not included in this study, the emissions factors were for all wetlands fitting this profile within the study. What is clearly seen in the figure is the difference between wetlands with altered and unaltered hydrology – it's clear the carbon emissions are much lower, and in most cases negative, for unaltered wetlands. Wetlands that have been altered have higher emissions, due to the oxidization of soil carbon, thus are net emitters of carbon in each study. Further, the uncertainty is higher for wetlands with altered hydrology. While it is unclear why that is, possible explanations could be a higher variability within emissions of altered wetlands due to variability in the amount of drainage throughout a site.

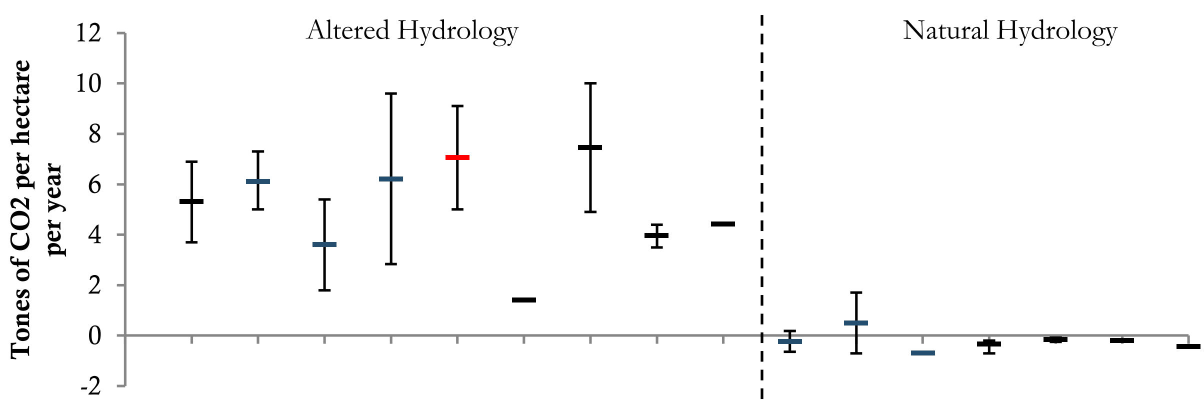

Figure 9 Emissions factors for wetlands with organic soil, divide based on hydrology. Altered hydrology implies some form of anthropogenic drainage. IPCC factors have blue bars; the Swiss factor has a red bar.

Mineral soil

There were the least data points for wetlands with mineral soil. Switzerland has not adopted any values for mineral soil, and the IPCC has only adopted one value for croplands and for wetlands. However, based on the low emissions, as show in Figure 10, perhaps the lack of research is justified.

On the other hand, the IPCC value for cropland qualified wetlands as net emitters, even to a small degree, while the other sources qualify these areas as sinks, thus Switzerland may benefit by conducting a local study in order to understand what the trends are for this area. This is especially true in the study area, where so many mineral wetlands are being used for agriculture.

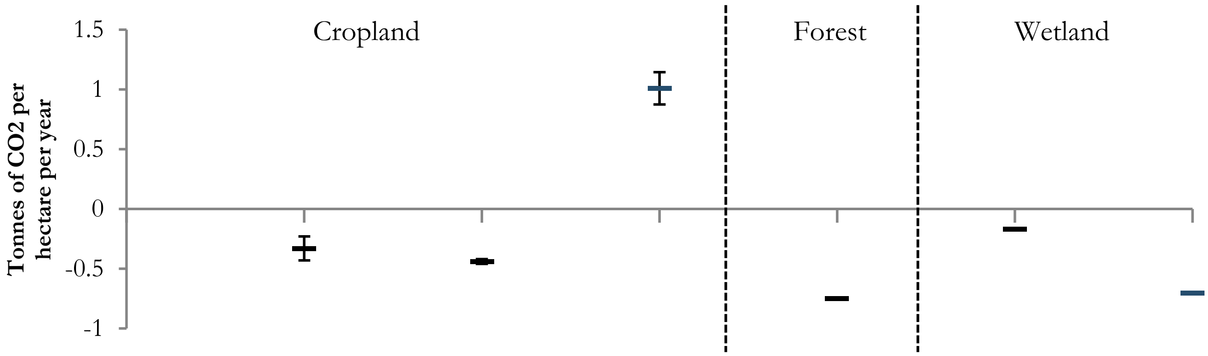

Figure 10 Emissions factors for areas with mineral soil. IPCC factors have blue bars.

Carbon footprint calculation

This study looks at the carbon sequestration rate of Kanton Zürich's wetlands, looking at both total wetland area as a whole and the individual wetlands. The method used to determine the carbon footprint is based on the IPCC's 2013 Guidelines. Based on the range of emissions factors, two sources of uncertainty were considered: the uncertainty within each source and the uncertainty between sources. The uncertainty was treated differently for total and individual carbon footprint estimates.

Total carbon footprint

In this case, the total carbon footprint refers to the sum of the carbon emissions from the total area of wetlands in Kanton Zürich. By summing the carbon emissions, wetlands that are carbon sinks cancel out the emissions from those that are net emitters. The formula provided by the IPCC, and common to many carbon footprint calculations, is seen in Equation 1.

$$Total\ tCO_2\ yr^{-1} = \sum_{i=1}^{n}(EF_{Type\ of\ wetland\ i} * Area_{Wetland\ i})$$

Equation 1

where the rate of carbon sequestration is expressed are tonnes of CO_2 (tCO_2) per year, EF represents the emissions factor for a specific type of wetland, and area is the size of that wetland in hectares.

Due to the wide range of potential emissions factors, the total carbon footprint calculation provided an opportunity to investigate the effects of different emissions factors on the final results. The emissions factors and uncertainty were treated as follows. First, uncertainty was added to the 10 out of 38 emissions factors that didn't include uncertainty. This is based on the assumption that the carbon sequestration rate is inherently an uncertain factor thus some amount of error should be considered. A standard value for uncertainty was assigned based on the median of the proportion of the uncertainty of the emissions factors sources. The resulting value was approximately ±33% of the carbon sequestration rate. For the others, the uncertainty used in the literature source was used.

Next, an emissions factor for each wetland type was selected. Due to the range of sources available for each wetland type, four trials were run assigning emissions factor sources in the following ways:

1) Random: Source are randomly selected from the full suite of available sources;
2) Prioritizing IPCC values: if an IPCC source is available for a wetland type, it will be selected. If an IPCC value is not available, another source is randomly selected from the existing options;
3) Prioritizing Swiss values: Swiss values are selected where available; random sources are used where not available; and
4) Prioritizing Swiss and IPCC values: Randomly selected Swiss and IPCC values are prioritized, other values are used where Swiss and IPCC numbers are not available.

Next, the Monte Carlo method was used to select both the emissions factor source (based on the selected prioritization scheme) and the emissions factor value (Metropolis & Ulam, 1949; Olivetti, Duan, & Kirchain, 2013). The emissions factor value was chosen by drawing a random number out of the range of possible numbers defined by that emissions factor's uncertainty. Based on Equation 1, a set of emissions factor sources were selected, a value was determined for each wetland based on a randomly selected emissions factor, then the results were totaled. This model was run one million times for each prioritization scheme, resulting in a probabilistic distribution of the total carbon footprint. Through this process, an optimal set of emissions factors could be determined and an estimate of the total carbon footprint of the wetlands can be determined including uncertainty.

Individual wetlands areas

To find the carbon footprint of an individual wetland, as with the total carbon footprint, the selected emissions factor is multiplied by the area of the wetland, characterized by land use, soil type, and hydrology, as show in Equation 2.

$$tCO_2\,yr^{-1} = EF_{Wetland\,Type} * Area_{Wetland}$$

Equation 2

where the rate of carbon sequestration is expressed as tonnes of CO_2 (tCO_2) per year, EF represents the emissions factor for a specific type of wetland, and area is the size of that wetland in hectares.

Due to the large number of wetland sites, completing a probabilistic assessment for each site was not feasible, but uncertainty was still considered in two ways. First, the full range of uncertainty within all appropriate emissions factors was considered; the minimum, mean, and maximum values were used. As such, no particular factor was prioritized and all values were considered. In this way, the full range of potential emissions can be understood, giving practitioners a broad range of values for a particular site. Secondly, the data were considered prioritizing the Swiss and IPCC numbers. If Swiss and IPCC numbers were available for a wetland type, the minimum, mean and maximum values of only the Swiss and IPCC numbers were included, excluding all other factors. If there were no Swiss or IPCC values available, the minimum, mean and maximum values of the existing factors were included. By using this method, the trends for each wetland type can be observed, and hotspots can be recognized.

Restoration Scenario Analysis

These values were also used to conduct scenario analyses to understand how the carbon footprint could change with restoration activities. In this case, the scenarios were defined as restoring natural hydrology conditions: removing man-made drainage ditches to allow natural water flow and returning wetlands that are being used for agriculture to natural wetland conditions. To reach this estimate, emissions factors were used for the land use and hydrology area that it would become after restoration. In this case, drained areas would become undrained wetlands and croplands would become wetlands. The results from the scenario analysis provide a basis for prioritizing sites for restoration based on greenhouse gases. The result could be further refined for an individual site based on a more detailed site conditions analysis and/or using a specific desired emissions factor.

Results

The results section is divided into three parts. The first describes the results of the wetland classification, providing a look into how the Kanton's wetlands have changed since 1900 based on the current land use and hydrology within the study area. The second gives an overview of the total carbon footprint calculations, discussing the significance of the value as well as the impact of the emissions factor employed. Finally, the individual carbon footprints will be discussed, including the results from the scenario analyses.

Wetland Characterization

A summary of the wetland types and their areas found within the study area is shown in Figure 11. Both the number of sites and the area are included, since they both provide interesting information. For example, there are far more sites with mineral soil than organic soil; however, considering the total area, the two soil types are close to equal. This highlights that wetlands with mineral soil are typically smaller in area compared with wetlands with organic soil. Mineral soil areas remaining as

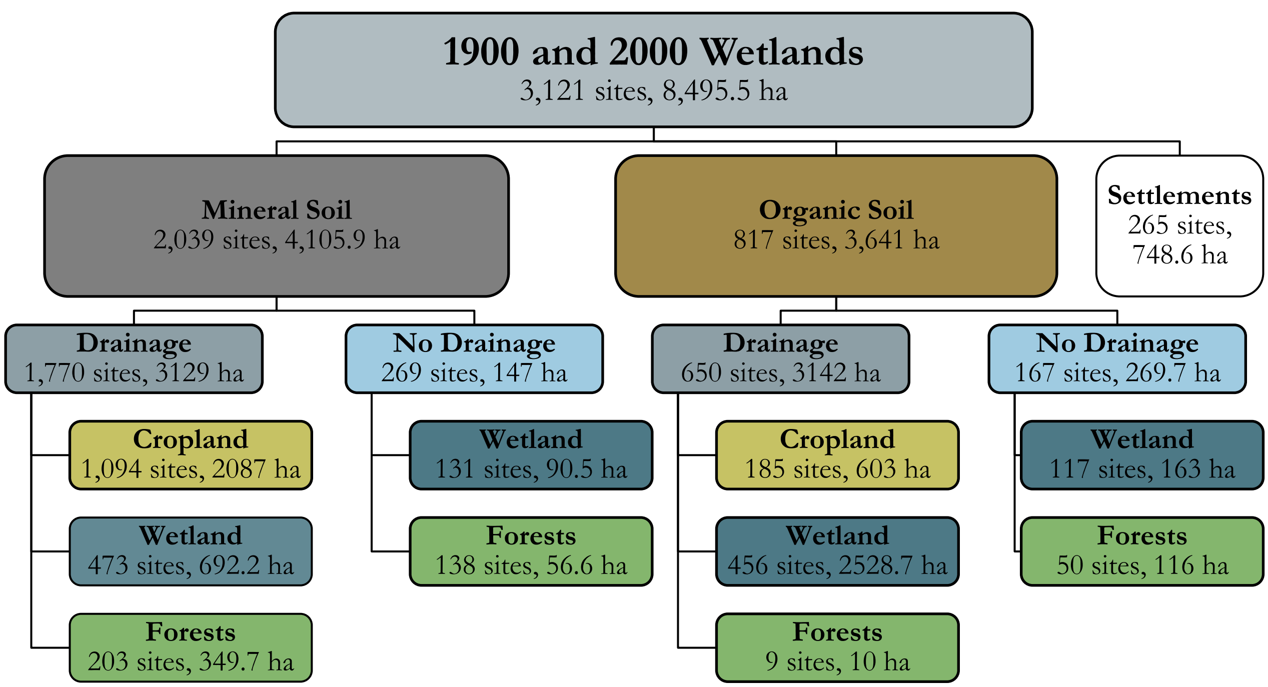

Figure 11 A summary of the types of wetlands found within the summary area, expressed by the number of sites and the total area in hectares.

wetlands or forested wetlands make up only 13% of the study area, and only 2% of that area is unaltered. In comparison, wetlands with organic soil (forested and peatlands) make up 33% of the study area, though the majority of these areas have also been altered. Figure 12 shows the distribution of wetland size; the x-axis, on a log-10 scale, demonstrates the large number of smaller sized wetlands.

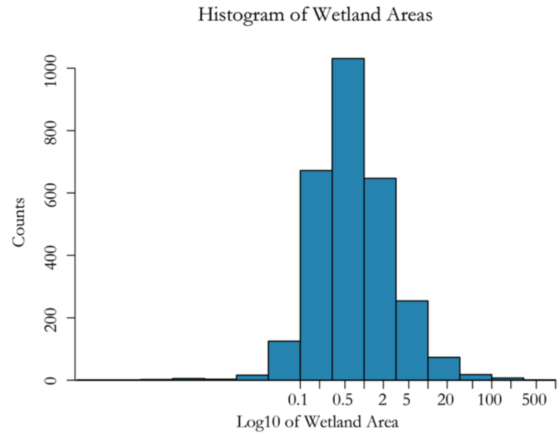

Figure 12 A histogram displaying the size of wetlands, in hectares, on a log-10 scale

As discussed by Gimmi et al, a large number of wetlands have been converted for agriculture; indeed 37% of sites are now farmed in some way, accounting for 32% of the total area. Wetlands with mineral soil have been disproportionately affected; roughly half of these areas are being used in agriculture. Altered hydrology is pervasive throughout the study area. Drainage was identified within 79% of sites and 83% of total area (including settlements); drainage was observed in 72% of wetlands that remain as natural areas. Thus, even wetlands that are now protected by law or conserved as natural areas show some signs of anthropologic disturbance.

In addition to the characterization for the carbon footprint calculation, the protection status and the existence of a grassland were added as extra relevant descriptors that are relevant for restoration scenarios. In total, 1,144 protected sites were identified, or roughly 85% of all remaining wetland sites covering 40% of total area. A total of 970 sites were characterized as grasslands, making up 23% of the total wetland area. A snapshot of the current state of the wetlands present in 1900, as well as any wetlands that have formed since then, is shown in Figure 13.

Total Carbon Footprint

As described above, the total carbon footprint for the extent of Kanton Zürich's wetlands was

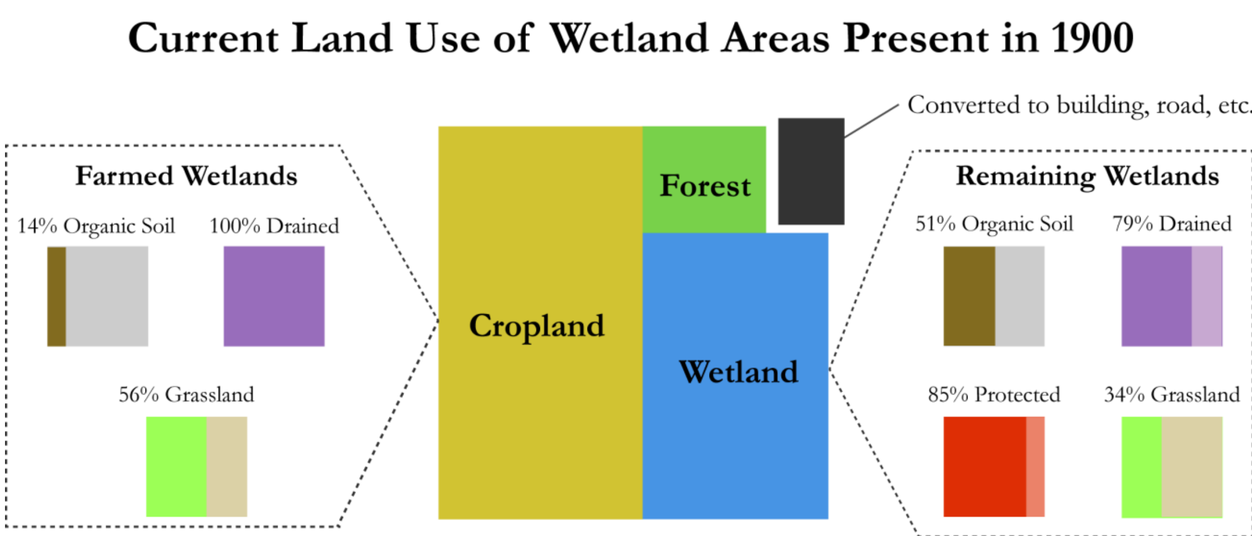

Figure 13 Main square: the current land use of wetlands that were present in 1900; in pop-out boxes: additional characteristics of focal wetlands, those that remain natural (right) and those that are presently used for agriculture (left).

estimated considering the uncertainty in the emissions factor used and the uncertainty within the emissions factor itself. Scenarios were evaluated based on four combinations of emissions factors sources: all possible sources, prioritizing IPCC sources, prioritizing Swiss sources, and prioritizing Swiss and IPCC sources. The results from the Monte Carlo tests, run one million times for each scenario, are shown in Figure 14 as histograms and box plots. For each histogram, the x-axis expressing the range of potential carbon emissions based on each combination of sources and the y-axis showing the frequency with which the values were found. The boxplots display solely the carbon emissions, with the box displaying the range of the first and third quartiles as well as the median carbon footprint, and the whiskers displaying the minimum and maximum results.

The figure shows an increased level of certainty when a subset of the factors are employed, demonstrated by the tighter distributions and increased frequency around certain values. For example, the IPCC-prioritized factors have a particularly high frequency level while the Swiss-prioritized factors have a lower frequency but a tighter distribution. Of significant interest is the existence of potential negative values, albeit a small probability, when considering the full uncertainty within Swiss-prioritized or every factors. When prioritizing the IPCC and Swiss-IPCC sources, the result leads to only positive values. This implies that when using UN-vetted factors, the total carbon footprint remains as a net source of carbon, never a net sink. This is an important consideration when considering wetland carbon as an offsetting mechanism, where being a net sink or a net source of carbon, and to what degree, is at the very core of the system.

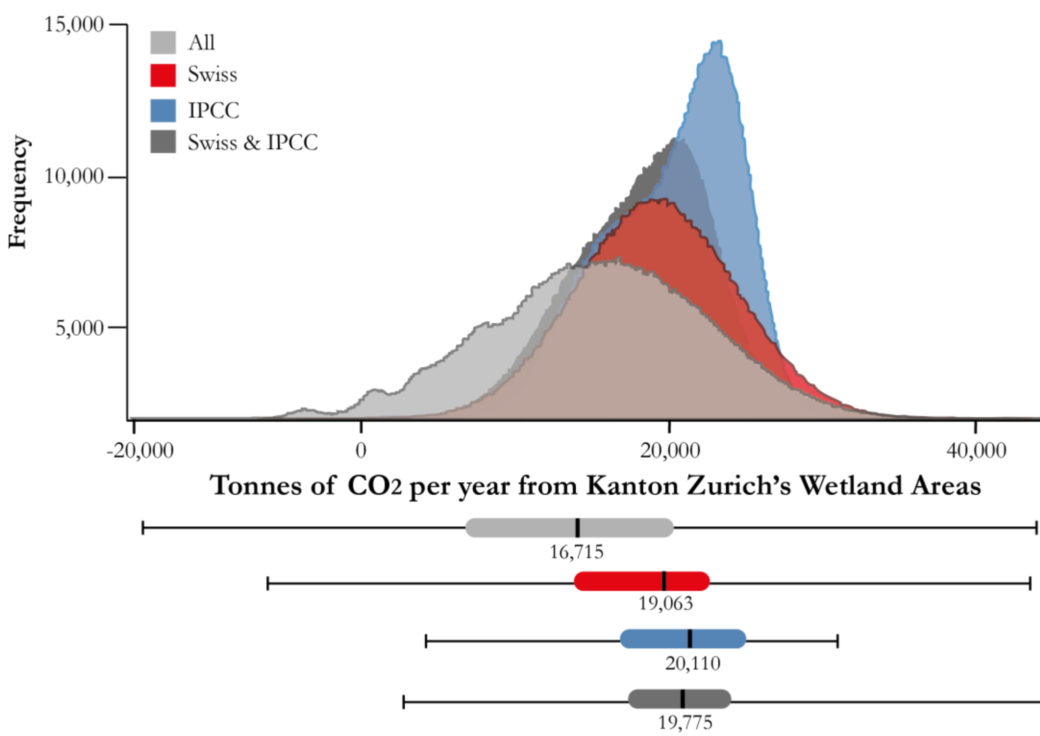

Figure 14 This set of histograms displays the uncertainty in the total carbon footprint of Kanton Zürich's wetlands. The distributions are based on random sampling within emissions factors from various sources.

The Swiss, IPCC, and Swiss-IPCC factors approach a similar mean value, between 19,000 to 20,000 tonnes of CO_2 emitted per year. Based on the importance of the Swiss and IPCC numbers in a political sense, this range likely approaches a sufficient median value for Kanton Zürich's wetlands carbon emissions. However, the median alone does not provide an understanding of the uncertainty within the values, the uncertainty must also be provided. To do this, the standard deviation within the carbon footprint estimates was found, as shown in Table 2. To average the numbers together while still accounting for uncertainty, the proportional uncertainty is calculated then averaged. Thus, the average estimate for the total carbon footprint is 19,649 tCO_2 per year ± 20.9% (or 4,106.6 tCO_2 per year). This number is very close to the Swiss and IPCC prioritization scheme. A benchmarking exercise is included in the discussion to add relevancy to these numbers.

Table 2 Uncertainty within carbon footprint estimates

Sources	Emissions (tCO_2 per year)	Standard Deviation	% Error
Swiss	19,063	4,863.29	± 25.5%
IPCC	20,110	3,316.25	± 16.5%
Swiss and IPCC	19,775	4,107.86	± 20.8%
Average	**19,649**	**4,106.6**	**± 20.9%**

While the total carbon footprint is interesting for understanding the overall impact of Zürich's wetlands, it is not relevant for reporting, which is generally associated with land use change. However, it is useful for illustrating the importance of emissions factors choice as well as the potential to account for and represent uncertainty. The next section dives into carbon footprinting related to individual wetlands and their potential for restoration.

Individual Wetland Carbon Footprints

The individual wetland carbon footprints were found using the full range of potential emissions factors, as well as the Swiss and IPCC prioritized factors. In this way, the relative importance of a wetland's type can be understood without a significant burden in terms of the probabilistic assessment for each individual wetland site. While the results cannot be totaled to reach the same numbers as the carbon footprint, this method allows us to draw out hotspots within wetland types, allowing for a better understanding of the priorities for restoration.

Because of the large number of individual wetlands in the study area, the results shown in Figure 15 represent the cumulative emissions by wetland types, categorized by land use, soil type and hydrology, and pertinent wetland characteristics. The solid lines represent the full range of uncertainty within all emissions factors; the hollow lines represent the Swiss and IPCC prioritized values; and the vertical blank bars represent mean values. Both assessments illuminate clear hotspots.

Wetlands with organic soil and altered hydrology have the highest impact, which was expected due to the increased carbon emissions associated with draining wetland areas. Covering less than 43% of the total area of wetlands, drained organic wetlands make up a lion's share of the total emissions. Comparing the range of uncertainty, the potential emissions based on all emissions factors is wider than that for just Swiss and IPCC factors, although the means are somewhat similar. The carbon footprint is definitively positive for both assessments and it is the clear emissions hot spot in the study area.

The second most impactful area is farms built on former wetland sites, particularly those with organic soil. In this case, the range of values demonstrates uncertainty within the emissions factors; both estimates include negative values, implying that it is possible for croplands to become a sink, not a source, for carbon. However, the mean emissions are positive; thus, most likely these wetlands are emitting rather than sinking carbon. Other wetland types that potentially contribute carbon emissions to a smaller degree, based on a positive mean value, are undrained organic wetlands, forested wetlands (drained organic and mineral soils and undrained organic soil), and croplands with mineral soil.

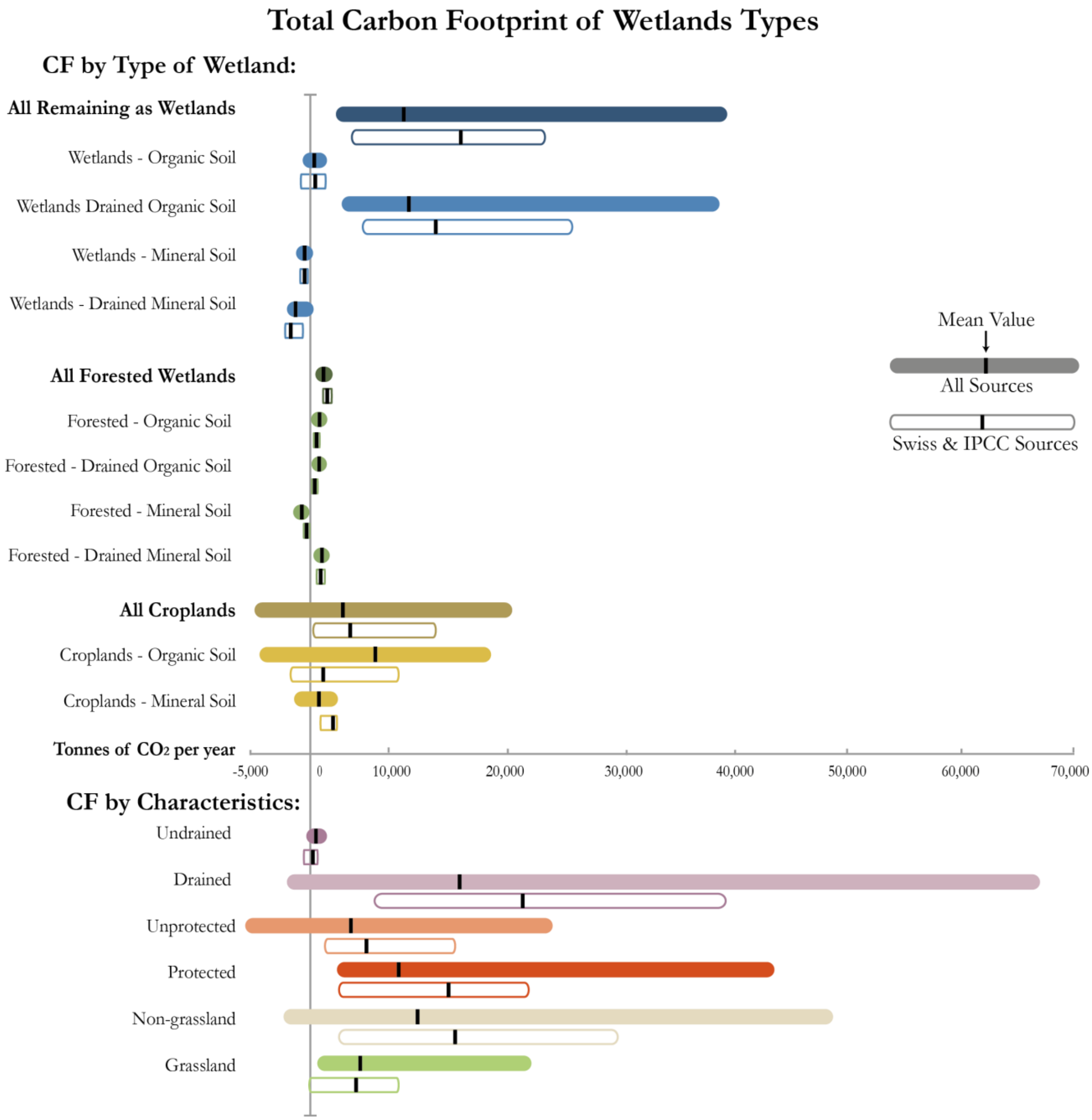

Figure 15 Carbon footprints of wetland types in Kanton Zürich. Solid represent the lowest and highest emissions based on uncertainty within all included emissions factors sources; hollow bars represent uncertainty within Swiss & IPCC emissions factors.

The second analysis included in the lower portion of Figure 15 is a breakdown of carbon emissions by the other relevant characteristics for restoration scenarios: altered hydrology, protection by law, and grassland presence. As with the analysis of wetland types, the Swiss-IPCC factors constrain uncertainty compared with all factors, though providing a similar mean to the full range of uncertainty. As would be expected, drained areas comprise the largest carbon impact. The range of values possible with all emissions factors is extremely broad, pointing to the wide uncertainty around the impact of altered hydrology; however, the Swiss-IPCC factors present a more constrained uncertainty with a squarely positive mean. Protected areas contribute an overall higher carbon impact, likely due to protected wetlands with altered hydrologic regimes. Non-grassland areas appear to contribute higher emissions than grasslands based on both factors.

Scenario Analyses

To understand the potential carbon benefits from restoration, a scenario analysis was conducted based on the results of the hot spot analysis above. The two prominent hotspots in Kanton Zürich's wetland types were wetlands with organic soil and altered hydrology and wetlands with organic soil that have been converted to croplands. Results were found by changing the emissions factors for each wetland fitting these conditions to those of the restoration conditions. In this case, only the uncertainty represented by the Swiss and IPCC emissions factors are considered. The results only consider emissions related to the focal wetland types, thus offsets relative to net sink wetlands are not included.

The first scenario converted the 2,529 hectares of drained wetlands with organic soil to their natural hydrologic conditions, "re-wetting" wetlands per the IPCC's terminology. To provide an additional aspect concerning the feasibility of restoration, results are grouped based on the area's protection status, assuming protected areas are easier to restore than unprotected and potentially privately-owned land. Whether an area is a grassland was also considered, a factor that could impact the cost and feasibility of restoration. The cumulative results, shown in Figure 16, again demonstrate clear

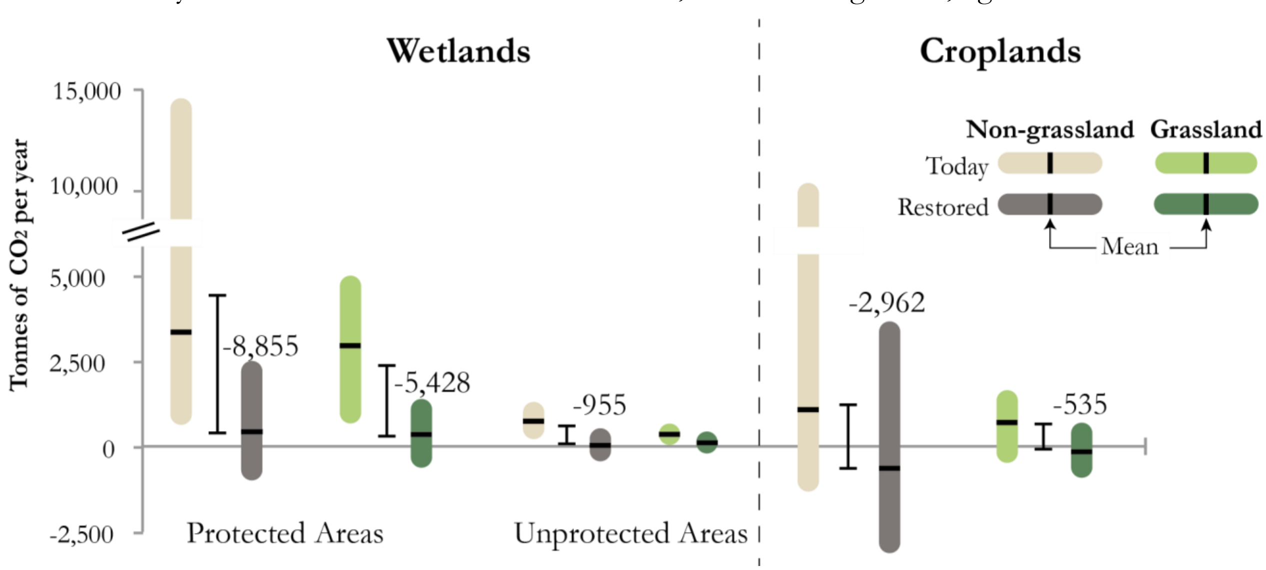

Figure 16 Scenario analysis results for the cumulative carbon footprint of wetland and cropland areas considered for the scenario analysis – darker lines refer to restored scenario; light lines refer to present conditions.

trends, with vertical lines showing the range of uncertainty divided by horizontal bars representing the mean value. The biggest potential benefit for restoration can be found within protected areas, with non-grasslands potentially providing the largest benefit, with a reduction in 8,855 tCO_2 per year, though the potential change in grasslands is also significant with a reduction in 5,428 tCO_2 per year. Unprotected areas provide a smaller benefit for restoration in terms of CO_2, with non-grassland areas accounting for the majority of the benefits, -955 tCO_2 per year.

The cropland restoration was conducted by converting croplands with organic soil, 131 sites with 90.5 hectares, to the wetland land use type. In this case, no division by protection status was included because croplands are assumed to be privately owned. The grassland/non-grassland distinction was included as with the previous scenario. The conversion of non-grassland croplands to wetlands resulted in the biggest benefit, 2,962 tCO_2 reduced per year. Croplands used as grasslands accounted for the smallest change.

Discussion

The results from this thesis demonstrate several pertinent points relating to the state of Kanton Zürich's wetlands, uncertainty within greenhouse gas emissions accounting, and wetland restoration prioritization based on ecosystem service quantification. Firstly, this thesis provides a snapshot of the current state of wetlands that were present in 1900, demonstrating ubiquitous alteration of natural hydrology, even in now-protected areas, as well as the widespread repurposing of wetlands as cropland or pasture. We found that, even considering the large uncertainty in emissions factors, it is possible to find a sufficient value to represent present carbon emissions. Furthermore, we observed that it is possible to uncover carbon emissions hotspots and estimate potential emissions reduction through restoration. Finally, we found that wetlands could be restored to contribute to greenhouse gas emissions reduction, thus proving some utility as infrastructure for climate change mitigation.

This section will discuss the state of Zürich's wetlands, the implications of the carbon footprinting results, and finally, feasibility of wetlands to act as infrastructure for climate mitigation through restoration. The discussion will also contextualize the results through spatial representation.

State of the wetlands

The results demonstrated that the changes in Kanton Zürich's wetlands have led to an increase in carbon emissions, along with changes in other ecosystem processes and habitat structures. Figure 17 shows the distribution of present land use, soil type and hydrology status through the Kanton.[1] Corroborating the results from Gimmi et al (2011), the majority of wetland areas have been drained to make room for human settlements or to provide room for agriculture, particularly in the southern and northeastern parts of the study area. Mineral wetland areas have been particularly affected by farming, with over three-quarters of sites present in 1900 now under agricultural conditions. While roughly even in terms of spatial distribution, mineral wetland areas have a smaller average size than organic sites, which could have contributed to the ease of their destruction. Furthermore, while several types of wetlands are considered ecosystems of national importance, Swiss wetland regulations define organic wetlands, namely bogs and moorlands, as critically endangered and endangered, thus providing them with a higher level of protection (Bundesamts für Umwelt, 2007a; The Swiss Federal Council, 1996). It is possible that the higher number of mineral sites that have been repurposed demonstrates this legal discrepancy.

Habitat loss and increasing fragmentation has implications for species diversity. Moorlands are important ecosystems especially in terms of species adapted to their specific conditions (Bergamini et al., 2009; Higgins, 2011; Hooftman & Diemer, 2002; Soomers, Karssenberg, Verhoeven, Verweij, & Wassen, 2013); in fact, a survey by the Swiss government showed that most moorlands are 50% covered by plant species that are rated as vulnerable, endangered or critically endangered (Klaus,

[1] Maps included in the Discussion and Results are stylized; see Appendix 3 for more detailed maps.

2007). However, wetland habitats in general, not only moorlands with organic soil, are compromised; waterbodies, watercourses and wetlands have the largest number of severely threatened species (Swiss Federal Office for the Environment, 2010). By these metrics, all wetlands should be protected, but by the metric included in this study, carbon emissions, again the moorlands rise to the top of importance.

Uncertainty within Carbon Footprint Calculations

This study aimed to understand the carbon emissions associated with the wetlands in Kanton Zürich using a widely-accepted method for calculation and reporting from the IPCC. The IPCC method is designed primarily for GHG-related land use change accounting, thus emissions factors drained or rewetted areas and constructed areas are the focus. In this way, the United Nations can lend guidance to GHG reporting and to the debate on carbon trading or offsetting programs related to wetland restoration or destruction. Such high level guidance works towards the adoption and acceptance of a standard method that can be used for benchmarking and comparison. The data within the IPCC method are based on literature, where it is common to quantify for status quo emissions, (such as in Bridgham et al., 2006; Mitsch et al., 2013), as well as change-based emissions, (such as with (Hediger, 2006; Janssens et al., 2005). Thus both static and flux-based studies provide important information for standardizing emissions factors and reducing uncertainty.

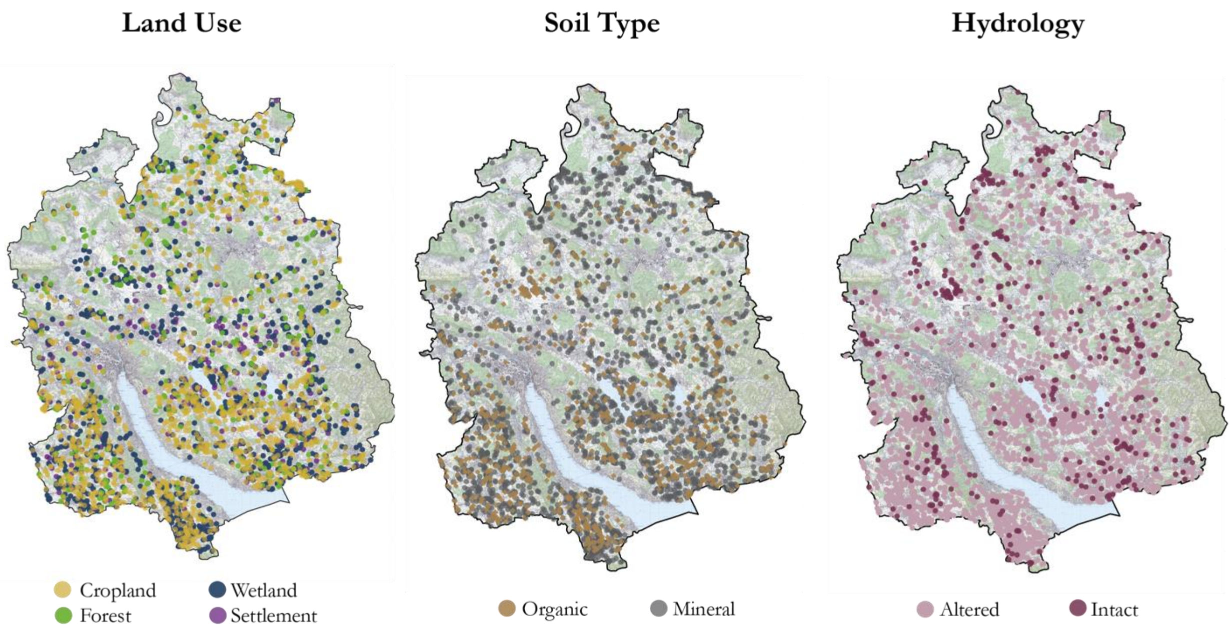

Figure 17 Spatial distribution of the primary characteristics of Kanton Zürich's wetlands. The points represent one site and are not representative of the wetland area.

By selecting the IPCC methodology and considering their emissions factors, we are able to understand how the method and subsequent results work in more detail as well as create a result that could be comparable to others using the same method. As per IPCC recommendations, we used the emissions factors provided within the 2006 and 2013 guidelines; however, additional emissions factors were employed in our study because not all wetland types within Kanton Zürich were not included – an issue that others undertaking such a study will likely find. Furthermore, the variability of the IPCC values and the generality of the factors (only specific to climatic scale, i.e., temperate or tropical) amounts to uncertainty that warrants further investigation. To add to the information provided by the IPCC, additional emissions factors sources were found that provide values for ecosystems mainly in Switzerland and Europe. Of local relevance are the emissions factors used by Switzerland for the GHG reporting. By including this wide range of emissions factors, we were able to complete a high level assessment of the wetland carbon footprint, pulling out hotspots that may contribute the biggest reduction if restored.

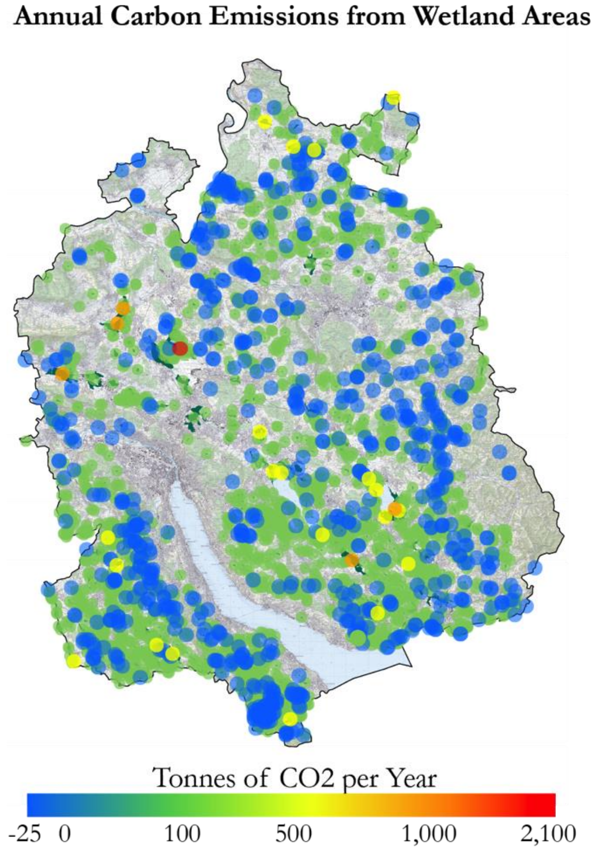

Figure 18 Spatial distribution of the individual wetland's mean carbon emissions found using Swiss and IPCC factors.

The method employed in this study is adopted from methods used for product carbon footprinting, a field that faces similar issues of resource intensive data collection and uncertain emissions factors (Olivetti et al., 2013). Most products have complex supply chains with many variables, each with their own set of emissions factors. To account for the range of uncertainty, and deduce a reasonable result, a probabilistic approach can help to highlight areas that are potential hotspots in emissions as well as guide one to topics where further research could be helpful. This study employed a variation on this idea for the total carbon footprint assessment by including a wide range of emissions factors and their associated uncertainties, then conducting analyses using subsets of emissions factors in order to hone in on an acceptable result and highlight hotspots.

The probabilistic assessment allowed us to see how uncertainty within and between the uncertainty factors affects the final results. When using the widest range of emissions factors, from all 38 sources, the total carbon footprint had a large range, including both positive and negative values, and skewed towards a lower mean value: 16,795 tCO_2 per year. Using Swiss, IPCC and a combination of the two sources led to relatively similar results though the probability of reaching a negative number was diminished when IPCC numbers are included, reducing the possibility of reporting a misleading result. Conducting the assessment with emissions factors as those created by the IPCC and/or Swiss agencies raised the mean total carbon footprint to between 19,000 and 20,000 tCO_2 per year, with a smaller range in uncertainty.

To further understand the more specific sources of emissions, individual carbon footprints were evaluated. In this case, the highest and lowest values of all emissions factors sources as well as Swiss & IPCC combined emissions factors were compared to represent the ranges of potential uncertainty. Through this method, hotspots can be clearly recognized, in this case clearly pointing to drained organic wetlands and croplands as the contributors of the largest amount of carbon emissions. Using the narrowed set of emissions factors subsequently decreased the level of uncertainty, though the mean values of both analyses were generally similar.

To visualize the distribution of carbon emissions sources throughout the Kanton, the mean carbon emissions of wetlands sites, found from the IPCC and Swiss sources, are mapped in Figure 18. Carbon emissions are relative to size, thus larger wetlands generally sequester or emit more carbon, though smaller wetlands add up to create a significant cumulative impact. Blue dots represent areas that are sequestering carbon; green, yellow, orange and red dots are carbon sources. The map highlights one wetland with a particularly high carbon footprint, the sole red dot, representing a large wetland destroyed for the construction of the airport. In fact, the one red spot is surrounded by a number of green spots, showing that it was not only one large wetland that was modified, but a group of wetlands of various sizes. Other hotspots include areas around the Pfäffikersee, Lützelsee, Haslisee and Greifensee as well throughout the highlands in the southern and northeastern areas of the Kanton.

Thus, for a high level analysis such as this one, a refined set of emissions factors was not necessary to understand the emissions hotspots; wide uncertainty still allows one to find a reasonable number for benchmarking and comparison. We found that Swiss and IPCC numbers, where available, are adequate for estimating hotspots and restoration potential, thus can be used to determine a reasonable value without further evaluation. However, if there is a need to find a more accurate emissions estimate, a probabilistic assessment could be conducted for each type of wetland, or individual wetland, similar to the total carbon footprint method. Alternately, to further resolve uncertainty, direct measurements could be taken on an individual site, such as a detailed assessment of vegetation cover, open water or grassland, additional soil sampling to confirm the coverage of organic soil, and on-site measurements of soil carbon as conducted by many of the literature sources included in this study, (e.g. Couwenberg et al., 2011; Freibauer et al., 2004; Hediger, 2006; Mitsch et al., 2012). Thus, this method offers a time-saving benefit by allowing one to use existing values and only conduct on-site measurements where needed.

Benchmarking

To lend a sense of real world understanding to the numbers discovered by the carbon emissions assessment, they can be compared to more commonly understood GHG emissions sources, a practice known as benchmarking (Schmidt, 2009). This process allows one to understand the relative impact of wetlands as well as put into context the potential reductions possible through restoration. We will consider the significance of the total carbon footprint, which includes the offsets garnered by wetlands that are net sinks of carbon, as well as the potential for restoration within the drained organic wetland scenario, the most promising restoration scenario. The benchmarking exercise is based on the two primary results. Firstly, the mean value for the total carbon footprint of Kanton Zürich's wetlands, 19,649 tCO_2 per year based on the IPCC and Swiss emissions factors, will be evaluated. Secondly, the potential reductions due to restoration of croplands are considered, also using the IPCC and Swiss-based factors.

Figure 19 demonstrates the range of potential emissions and reductions based on common emissions sources, found using U.S. Environmental Protection Agency's Greenhouse Gas Equivalency Calculator.[2] Comparisons are made to the number of passenger car's annual GHG emissions, kilograms of coal burned, and propane cylinders for barbeque consumed. For an economic comparison, the 2014 value for carbon adopted by the Swiss government, CHF 60, is used to monetize emissions; however it should be noted that this value is expected to rise in the coming years if emissions reductions targets are not met (The World Bank, 2014).[3] For simplicity, this figure represents only the mean values, not the full uncertainty; a full accounting of the high and low potential values can be found in Appendix 2.

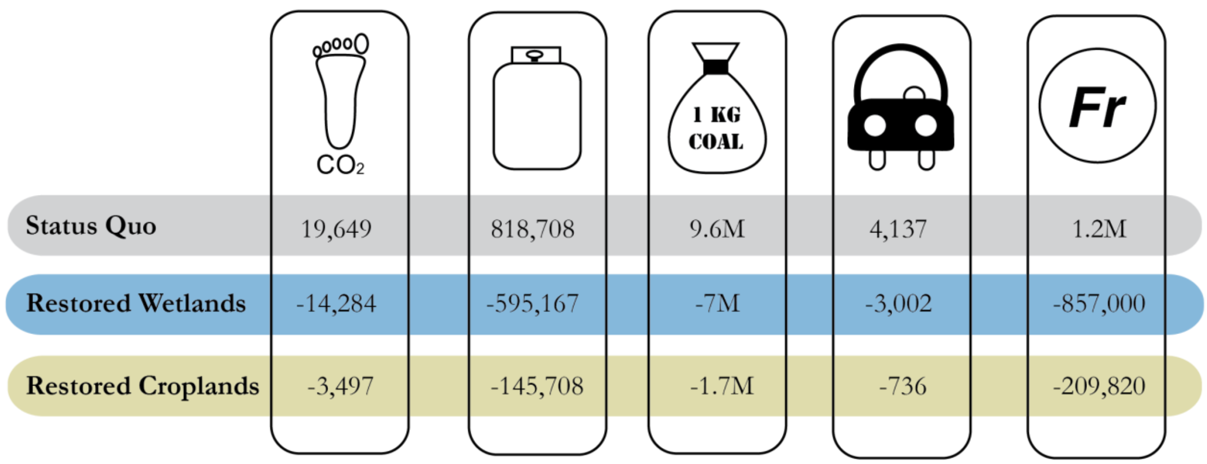

Figure 19 Comparisons of wetland carbon footprint values (first column, in tCO_2/year) with real word values: # of propane cylinders for barbeques, # of kilograms of coal burned, # of passenger car emissions for one year, and the value (in CHF) of carbon based on the Swiss carbon value of CHF 60 per tonne.

Wetlands and Methane

The emissions calculations discussed within this study only consider carbon dioxide emissions and sequestration. An in depth study of carbon allows for a full understanding of carbon emissions factors as well as carbon hotspots, though additional greenhouse gases, namely methane and nitrous oxide, should be included in a comprehensive greenhouse gas survey to further understand the GHG impact (Bridgham et al., 2006; IPCC, 2014a; Neubauer, 2014). Methane is the second most important greenhouse gas, following carbon, and wetlands are the largest source of emissions worldwide (Kirschke et al., 2013). However, methane emissions are shifting, complex and difficult to quantify, and can vary significantly, even within one wetland, based on wetland type, vegetation and seasonal hydrology (Turetsky et al., 2014).

Methane is often measured through the direct capture of emissions on a particular site, e.g. Mitsch et al. The IPCC's 2006 Guidelines considered methane emissions from drained organic soils as negligible but has now updated its estimates to consider ditches with organic soil as well as drained croplands as a potentially significant source of methane emissions, though guidance is provided for a

[2] http://www.epa.gov/cleanenergy/energy-resources/calculator.html

[3] Ecosystems are not included in the Swiss Emissions Trading Scheme presently; the carbon price is included for comparison purposes only.

range of wetland types (IPCC, 2014a). However, as with carbon, there exist the same issues of uncertainty within emissions factors, and, a lack of locally available factors. The IPCC (2014a) does include a set of emissions factors for methane based on literature, though a similar issue exists where not every type of wetland in Zurich is included. Bridgham (2013) notes a lack of understanding of the complex interactions between microbes, plants and methane, an area that requires further study to reach more reliable estimates. This uncertainty is reflected in the Global Carbon Project's 2013 Methane Budget, which uses an uncertainty value of 50% for methane in wetlands, representing the limits of methane emissions calculations (Global Carbon Project, 2013).

Different from a carbon study, the goals of a methane study must determine the time scale for which the study is relevant. If the immediate impact of emissions is desired, it is possible to replicate the methods employed in this study using studies that estimate spontaneous methane flux. These values can also be used for a longer timescale, but the lifespan of methane in the atmosphere must also be considered, which reflects a change in methane over time. Turetsky (Turetsky et al., 2014) and Bridgham (Bridgham et al., 2013) state that larger scale surveys of methane emissions are challenging due to a lack of information on the areas of wetland types, i.e. bog, fen or forested wetland. While Switzerland has this information, as employed by this study, Joabsson (1999) notes that even more detailed analysis of land cover (e.g. plant composition, water table) is necessary to capture the true picture of emissions. Though it is possible to undertake a study of methane following the methods employed here, similar to carbon, it would likely only uncover potential hotspots, and less so capture accurate long-range emissions unless time is added as a metric within the study.

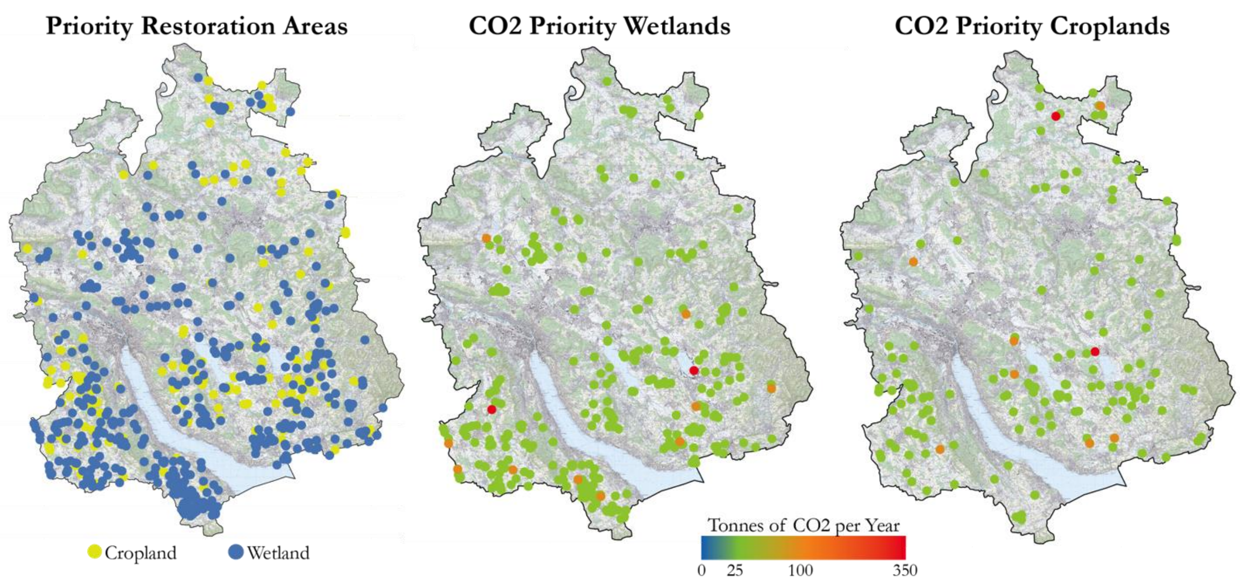

Figure 20 Spatial distribution of areas prioritized for restoration: drained wetlands with organic soil and croplands with organic soil. The first figure shows the location of both types, the second and third figures show the range of carbon emissions of wetlands (middle) and croplands (right)

Wetlands as Climate Mitigation Infrastructure

Wetlands are clearly a vital habitat important to both the wildlife and the people of Switzerland. This study provided another rationale for their restoration – reducing greenhouse gas emissions. Under the present conditions in Kanton Zürich, the wetland areas as a whole are most likely acting as a net source of carbon emissions, though individual areas may be net sinks. However, real benefit can be found within the restoration scenarios due the large area of drained peatlands in the Zürich region. Restoring peatlands can reduce annual carbon emissions equivalent to the emissions of over 3,500 passenger cars per year. While wetlands don't emit the harmful chemicals from vehicles, they contribute a preventable burden to global greenhouse gases emissions.

Figure 20 shows the spatial distribution of the carbon emissions for the subset of wetlands prioritized for restoration. The highest amount of potential carbon mitigation per year can be found within four sites that could potentially mitigate over 300 tCO_2 per year per site. For the wetland areas, the highest emitting sites were along the border of the Pfäffikersee and in the highlands near Bonstetten. A number of "orange level" sites were found around the Kanton, particularly in the southern regions, that could be combined to meet a larger level of mitigation. However, to reach the highest level of carbon mitigation, many smaller wetlands will need to be restored.

Drained wetlands with organic soil are contributing most significantly to carbon emissions; their distribution can be seen in more detail in Figure 21. The most significant reduction to emissions could be realized within areas that already are protected, conditions that most likely would have the least barriers for restoration since the government is already in ownership. Furthermore, restoration could bring additional benefits, such as expanding habitat for endangered or vulnerable species, as well as improving water quality and groundwater recharge. There is a chance that neighboring properties could potentially be affected from removing drainage ditches, thus the impact of restoring hydrology would have to be evaluated and potentially mitigated. Organic wetlands used for agriculture also contribute a larger share of greenhouse gases, though the degree to which this can be mitigated is much lower. Additional concerns must be considered for croplands, such as the trade-off in crop production or the cost of subsidies that could be required to repurpose land areas.

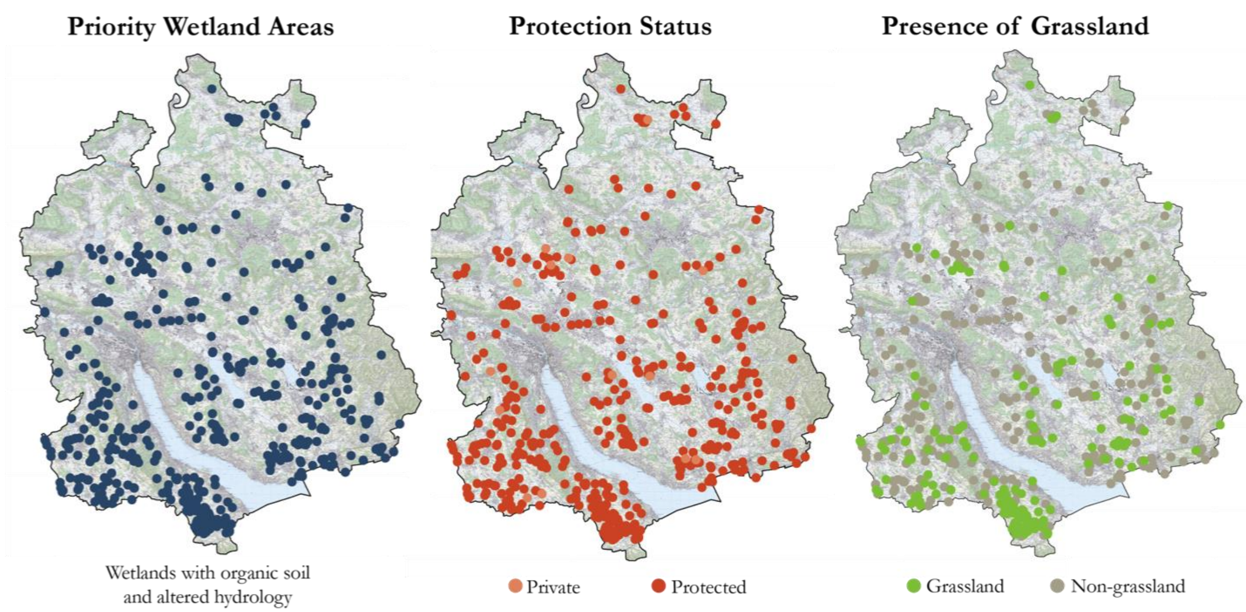

Figure 21 Overview of priority wetlands for restoration within Kanton Zürich

In terms of changes in methane emissions under these restoration scenarios, Turetsky's meta-analysis found that temperate bogs and fens with natural hydrology had particularly high methane emissions, based on spontaneous measurements, with those comprised of grasses and forbs contributing the most methane. Areas covered by shrubs and trees contributed 40 to 80 percent lower emissions respectively. The study found that, under experimental conditions in short-term studies, wetland drainage reduced methane emissions (14 sites) and rewetting raised emissions (6 sites), though it should be noted that none of the sites in the study were in or near Switzerland. However, longer terms studies suggest that, while emissions in the short term may rise, over a longer period wetlands with restored hydrology will approach a level in which carbon sequestration overtakes methane emissions, and the wetland becomes a net sink (Bridgham et al., 2013; Whiting & Chanton, 2001). Thus the significance of an increase in methane emissions following restoration should be considered and quantified, but also benchmarked to understand its relevance on a global and temporal scale.

The results for Kanton Zürich reflect the conditions common throughout many areas of the temperate European continent. Carbon emissions resulting from widespread wetland conversion over the last century may be able to be reduced through restoration (Janssens et al., 2005). Valuation of emissions reduction-related restoration is possible, but of course depends on the emissions factors selected to make the calculation. Using IPCC and Swiss values will produce a value that meets international criteria for acceptance. If more accuracy is desired, one could conduct tests on focal wetlands to understand their rate of carbon storage more precisely, though this is a potentially costly and time-intensive process.

If further prioritizing of wetlands for restoration is needed, due to, for example, budgetary limitations, secondary or tertiary metric for understanding the wetlands' benefits could be quantified using this method, such as habitat for endangered species, protection of a waterbody, or flood mitigation. By adding additional layers, even considering an uncertain range of values for emissions reductions, one could add a broader perspective for prioritizing restoration. In Zürich, this could be done using existing spatial datasets in the same way the GHG quantification was done, without a need for additional site visits. For example, within this study, we could add layers for endangered species then couple hotspots for species with hotspots for emissions. This allows for an even more drilled down prioritization scheme, reducing the time for primary data collection in the field. Perhaps in Kanton Zürich, a relative small area, this might not be necessary, but for a region- or country-wide initiative, this would certainly streamline decision-making and focus limited resources.

The emissions reductions found within this study are merely an estimate to understand potential reductions; the next section will describe the benefits and limitations of such a study, and how improvements could be made.

Conclusions

This study considered the potential to use ecosystem services as a tool for prioritizing wetland restoration with the goal of climate change mitigation. To meet that end, a case study was developed to estimate the carbon emissions of the wetlands in Kanton Zürich. This method is particularly relevant at this time due to the 2014 release of an updated set of IPCC's Guidelines for the calculation of carbon emissions from wetlands. The IPCC provides a set of emissions factors that estimate the carbon emissions from certain wetland types based on scientific literature. The guidance is meant for reporting GHG reductions or emissions related to land use change, but could also be used for calculating carbon offsets. Per their guidelines, practitioners can use solely IPCC emissions factors or select their own that are tailored to a specific location. Switzerland, for example, has adopted a set of wetland-related emissions factors that includes values based on studies conducted within Switzerland as well as the more generic IPCC values.

To understand how the selection of emissions factors affects uncertainty within the ultimate wetland carbon footprint value, this study expanded the range of potential emissions factors offered by the IPCC to include additional emissions factors used by the Swiss government as well as relevant literature sources. This method allowed for an additional understanding of the uncertainty within carbon footprinting of wetlands that appears to be common throughout literature. Such uncertainty contributes to an underlying ambiguity that has thus far precluded wetlands from being considered for ecosystem-based carbon offset programs like REDD+, where a definitive value for emissions reduction must be realized and trusted. Using a probabilistic approach, we were able to understand how uncertainty within and between emissions factors affects the carbon emissions estimate for all wetlands in the study area. We found that Swiss and IPCC emissions factor values lead to similar values for the total carbon footprint, thus demonstrating the validity of using both sets of factors when also including a numeric disclaimer of uncertainty. In this study, we aggregated the uncertainty found within each emissions factors source used in each analysis, which averaged between 20-30%.

Explicitly stating the uncertainty value, and how it was determined, is an important aspect for the practice of wetland restoration for climate change mitigation to gain acceptance and credibility within ecosystem accounting. Similar to issues around product carbon footprinting, in which businesses, governments or retailers wish to assign a simple carbon footprint to a product as an eco-label, the truth is that many of these analyses are simply best guesses often based on a vast set of uncertain data (Greene, Kirchain, & Olivetti, 2012). In reality, similar to a nutrition label on a cereal box, an accurate carbon footprint value that describes exactly what is in that box is not realistic – transport methods, suppliers and materials change, raising or lowering the GHG emissions. To find a number for each individual product would be too time and resource intensive, thus a number must be agreed upon that represents an average product.

In the same way, for wetlands, it would be time consuming and costly to evaluate each of the 3,000+ wetlands included in this study area to find a specific carbon sequestration rate for each one. Generalized emissions factors offer a solution here, such as those adopted by the government of Switzerland. However, many variabilities still exist. Beyond having varying rates of carbon emissions or sequestration, many wetlands have seasonally changing patches of open water, which could vary seasonally, that impact this rate (Mitsch et al., 2013). Further, the types of plants covering a wetland can alter emissions; some plants, such as sedges, may conduct higher amounts of GHGs from the soil to the air (Joabsson et al., 1999; Turetsky et al., 2014). Wetlands in this study are categorized from a coarse-grained level, they are classified with one land use per area, while in reality there may be patches of trees or sedges, or pockets of mineral or organic soil, that could change the actual carbon footprint.

Even more complicated to represent is the rate of emissions for drained organic wetlands, which were found to have the highest carbon footprint in this study. A wetland that is newly drained may emit more carbon than one that has been drained for 50 years (Mitsch et al., 2012). Since this study considered wetlands at the years 1900 and 2000 only, the precise date of drainage is unknown and unaccounted for, thus the impact of drainage could be over- or underestimated. The emissions factors used for drained organic wetlands have the highest range of uncertainty, but without further study it is unknown to what degree this uncertainty is accurately represented within the included emissions factors.

The relative efficiency of this method, relying on existing data and studies to find a sufficient result, demonstrates the potential of decreasing the time and effort to conduct analyses used for decision-making. Even with a wide range of uncertainty, trends in emissions could be clearly seen. Using a range of emissions factors allowed for comparison of emissions between wetland types, allowing hotspots to emerge. Hot spots demonstrated the potential to prioritize wetland restoration based on generalized estimates of emissions, in this case, a combination of the Swiss and IPCC emissions factors. Coupling the values with a spatial analysis allows one to clearly see the exact areas that should be prioritized for restoration. The mapping exercise also demonstrated the location and distribution of areas within Kanton Zürich would need to be restored to make a large difference, potentially representing a significant monetary investment. If only a smaller subset of wetlands could be feasibly restored, it would be beneficial to combine these hotspots with other ecosystem service hot spots, ideally using data already recorded by academic or government bodies.

While the methods employed here provide promising results, the study has a number of limitations that require further attention. Firstly, this study does not include greenhouse gases that could accentuate or reduce emissions shown within this study. Methane and nitrous dioxide are two important GHGs that wetlands would be affected by both drained and re-wetted scenarios. This study would be further improved if these GHGs were considered using the methods described here. The element of time is also a limiting factor. This study looked at the present conditions of wetlands, not taking into account how long an area has been in the present state. Further, when an area is restored, the rate of carbon sequestration or emissions could shift over time, thus using a static emissions factor, for any GHG, does not necessarily represent the conditions at the present moment, or the conditions over a longer period of time. Though, as mentioned before, the study provides an estimate to be used for hotspot analysis and restoration prioritization, thus some factors must be simplified to meet a sufficient result in a reasonable amount of time. As mentioned previously, more detailed studies are always possible on areas that were identified as the highest emitters.

Recommendations

This study showed the possibility to understand hotspots in wetland carbon sequestration using emissions factors that include a wide range of uncertainty. Using a more targeted set of emissions factors, such as from the IPCC, allows for a more constrained estimate, though the applicability for one particular site may be difficult to determine without further on-the-ground testing. While the IPCC recommends developing a set of emissions factors for a country or region, we found that the Swiss and IPCC numbers led to similar results. This may be different for other regions, however, and can be tested following these methods to understand the resulting impact on carbon footprint values.

That said, the numbers found within this report likely represent acceptable values in terms of IPCC Guidance and thus should be valid for reporting purposes. The IPCC has been tasked with providing information on how to reach a reasonable number for wetland GHG emissions. Some countries may have limited resources for conducting studies on GHG emissions. Thus the IPCC provides a generic set of values that can be considered, some of which include uncertainty. However the lack of information on wetland types not prioritized by the IPCC leaves a gap that may be challenging to sufficiently quantify.

While there may not be a specific need to understand the emissions of all types of wetlands, it is valid to understand how land use changes over time and how that impact is reflected by a variety of measures. In this era of climate change, GHG emissions from all types of sources are an important political and societal topic and thus should be measured and reported. Furthermore, for programs like REDD+, wetlands, and particularly forested wetlands, may become a valid area for consideration in the future. However, this study found that the IPCC does not use an updated number for forested wetlands – solely relying on a 2003 estimate that pertains only to forests in general, not differentiating soil type, numbers that Switzerland has also adapted. While this number may be accurate, there is still a potential benefit to better understanding carbon sequestration within Zurich's many forested wetland areas, and looking for carbon benefits from restoring forested wetlands that have been logged or rewetting forested wetlands that have been drained. Restoration of these areas could represent a cost-effective technique with wide-ranging benefits.

In the same vein, methane emissions for Swiss wetlands should also be considered and quantified through a set of standardized methane emissions factors. It is possible that drainage ditches emit high levels of methane, thus there is an argument for mapping these areas and determining ways to reduce these emissions. Switzerland may wish to consider the time scale of emissions as well. With the importance of mitigating emissions today in order to reach short-term emissions reductions goals, short-term emissions reductions may be more important than long-range emissions, and it may become more relevant to make this type of distinction. As the IPCC's Climate Change 2014 report states (2014c), the time is now to realize emissions reductions worldwide, and based on the findings of this report, wetland restoration of a large scale could contribute to this goal while also providing a range of other benefits to society and the environment as a whole.

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Appendix 1

A full accounting of the emissions factors and their data source are compiled below, organized on a high level by land use, with the additional characteristics of soil type and hydrology as secondary and tertiary factors.

Land Use	Soil Type	Hydrology	CO_2 per hectare per year	Uncertainty		Source
				Low	High	
Cropland	Organic	Drained	0.2	0.00	0.63	IPCC 2003 Good Practice Guidance for Land Use, Land-Use Change and Forestry, Table 3.5.2.
Cropland	Organic	Drained	1.1	0.03	2.90	IPCC 2003 Good Practice Guidance for Land Use, Land-Use Change and Forestry, Table 3.5.2.
Cropland	Organic	Drained	3.5	2.20	31.00	Freibauer, A., et al. (2004). Carbon sequestration in the agricultural soils of Europe. Geoderma.
Cropland	Organic	Drained	10	1.00	19.00	IPCC. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*.
Cropland	Organic	Drained	9.5	7.30	11.70	Hediger, W. (2006). Modeling GHG emissions and carbon sequestration in Swiss agriculture: An integrated economic approach. International Congress Series, 1293, 86–95.
Cropland	Organic	Drained or wet	-6.5	-	-	Hediger, W. (2006). Modeling GHG emissions and carbon sequestration in Swiss agriculture: An integrated economic approach. International Congress Series, 1293, 86–95.
Cropland	Organic	Drained	5.5	4.10	7.60	Wetlands International. (2009) Emissions factors for managed peat soils: An analysis of IPCC default values.
Cropland	Organic	Drained	8.2	-	-	Couwenberg, J., et al. (2011). Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. *Hydrobiologia*, *674*, 67–89.
Cropland	Organic	Drained	11.9	-	-	Couwenberg, J., et al. (2011). Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. *Hydrobiologia*, *674*, 67–89.
Cropland	Organic	Drained	15.5	-	-	Couwenberg, J., et al. (2011). Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. *Hydrobiologia*, *674*, 67–89.

Cropland	Organic	Drained	5.3	-0.92	11.55	Agroscope, CO2 Emissions Factors of Bogs in Ag Use, 2011
Cropland	Organic	Wetland	4.9	3.3	6.5	Freibauer, A., et al. (2004). Carbon sequestration in the agricultural soils of Europe. Geoderma.
Cropland	Organic	Drained	7.9	6.50	9.40	IPCC. (2014). 2013 Supplement to the 2006 IPCC Guidelines for Greenhouse Gas Inventories : Wetlands. Geneva, Swizerland, Table 21, pp. 2.9-2.11
Cropland	Mineral	Drained or wet	-0.33	-0.43	-0.23	Hediger, W. (2006). Modeling GHG emissions and carbon sequestration in Swiss agriculture: An integrated economic approach. International Congress Series, 1293, 86–95.
Cropland	Mineral	Drained or wet	-0.44	-0.46	-0.42	Hediger, W. (2006). Modeling GHG emissions and carbon sequestration in Swiss agriculture: An integrated economic approach. International Congress Series, 1293, 86–95.
Cropland	Mineral	Drained	1.01	0.876	1.144	IPCC. (2014). 2013 Supplement to the 2006 IPCC Guidelines for Greenhouse Gas Inventories : Wetlands. Geneva, Swizerland, Table 5.2, page 5.12
Forested	Organic	Wetland	0.68	-	-	IPCC. (2003). *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* Geneva, Swizerland.
Forested	Mineral	Wetland	-0.75	-0.95	-0.55	Luyssaert, S., et ak (2010). The European carbon balance. Part 3: Forests. *Global Change Biology*, *16*, 1429–1450.
Forested	Organic	Drained	1.3	-	-	Höper, H. (2007). Emissions of Greenhouse Gases from German Peatlands. *Telma*, *37*, 85–116.
Forested	Organic	Drained	0.68	-	-	Agroscope, CO2 Emissions Factors of Bogs in Ag Use, 2011
Forested	Organic	Drained	2.6	2	3.3	IPCC. (2014). 2013 Supplement to the 2006 IPCC Guidelines for Greenhouse Gas Inventories : Wetlands. Geneva, Swizerland, Table 21, pp. 2.9-2.11
Wetland	Organic	Drained	3.95	3.50	4.40	Höper, H. (2007). Emissions of Greenhouse Gases from German Peatlands. *Telma*, *37*, 85–116.
Wetland	Organic	Drained	4.4	-	-	Höper, H. (2007). Emissions of Greenhouse Gases from German Peatlands. Telma, 37, 85–116.
Wetland	Organic	Drained	7.05	5	9.1	Rogiers, N., Conen, F., Furger, M., Stockli, R., Eugster, W., 2008. Impact of past and present land-management on the C-balance of a grassland in the Swiss Alps. Global Change Biology 14: 2613-2625.
Wetland	Organic	Drained	1.4	-	-	Leifeld, J., Gubler, L., Grunig, A., 2011. Organic matter losses from temperate ombrotrophic peat-lands: an evaluation of the ash residue method. Plant and Soil 341: 349-361.
Wetland	Organic	Drained	6.22	2.84	9.6	Agroscope, CO2 Emissions Factors of Bogs of National Importance, 2011

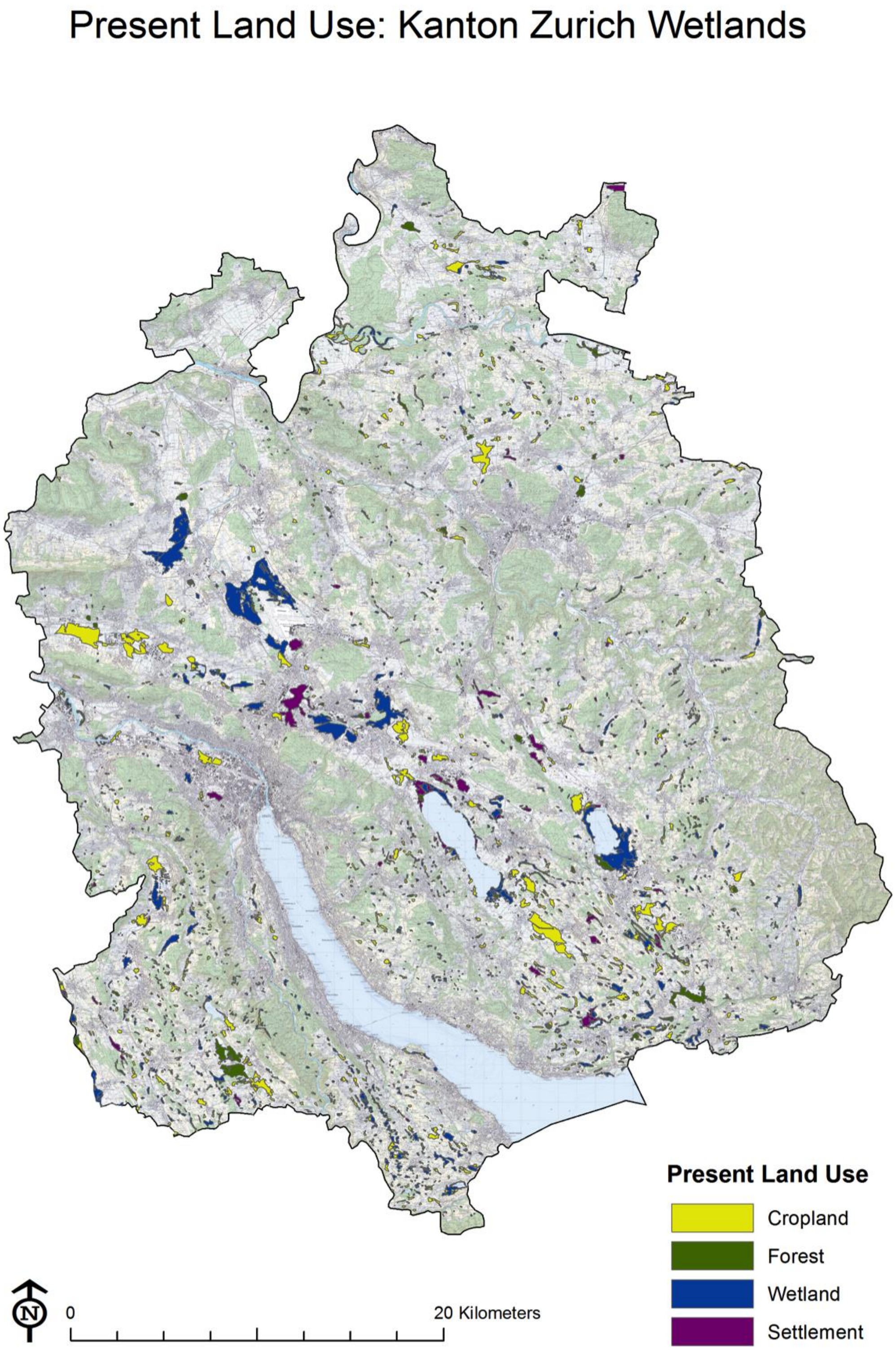
Wetland	Organic	Drained	7.45	4.9	10	Leifeld, J., Gubler, L., Grunig, A., 2011. Organic matter losses from temperate ombrotrophic peat-lands: an evaluation of the ash residue method. Plant and Soil 341: 349-361.
Wetland	Organic	Drained	5.3	3.7	6.9	IPCC. (2014). 2013 Supplement to the 2006 IPCC Guidelines for Greenhouse Gas Inventories : Wetlands. Geneva, Swizerland, Table 21, pp. 2.9-2.11
Wetland	Organic	Drained	6.1	5	7.3	IPCC. (2014). 2013 Supplement to the 2006 IPCC Guidelines for Greenhouse Gas Inventories : Wetlands. Geneva, Swizerland, Table 21, pp. 2.9-2.12
Wetland	Organic	Drained	3.6	1.8	5.4	IPCC. (2014). 2013 Supplement to the 2006 IPCC Guidelines for Greenhouse Gas Inventories : Wetlands. Geneva, Swizerland, Table 21, pp. 2.9-2.13
Wetland	Organic	Drained	9.6	4.5	17	IPCC. (2014). 2013 Supplement to the 2006 IPCC Guidelines for Greenhouse Gas Inventories : Wetlands. Geneva, Swizerland, Table 21, pp. 2.9-2.14
Wetland	Organic	Wetland	-0.2	-0.3	-0.1	Freibauer, A., et al. (2004). Carbon sequestration in the agricultural soils of Europe. Geoderma.
Wetland	Organic	Wetland	-0.35	-0.7	-0.2	Janssens, I. A., et al (2005). The carbon budget of terrestrial ecosystems at country-scale – a European case study. *Biogeosciences*.
Wetland	Organic	Wetland	-0.45	-0.65	-0.25	Hediger, W. (2006). Modeling GHG emissions and carbon sequestration in Swiss agriculture: An integrated economic approach. International Congress Series, 1293, 86–95.
Wetland	Organic	Wetland	-0.23	-0.64	0.18	IPCC. (2014). 2013 Supplement to the 2006 IPCC Guidelines for Greenhouse Gas Inventories : Wetlands. Geneva, Swizerland, Table 3.1.
Wetland	Organic	Wetland	0.5	-0.71	1.71	IPCC. (2014). 2013 Supplement to the 2006 IPCC Guidelines for Greenhouse Gas Inventories : Wetlands. Geneva, Swizerland, Table 3.1.
Wetland	Mineral	Wetland	-0.17	-0.255	-0.085	Bridgham, S. D., et al. (2006). The carbon balance of North American wetlands. Wetlands.
Wetland	Mineral	Wetland	-0.703	-	-	IPCC. (2014). 2013 Supplement to the 2006 IPCC Guidelines for Greenhouse Gas Inventories : Wetlands. Geneva, Swizerland, Table 3.1, page 5.12.
Wetland	Mineral	Drained	-0.33	-0.43	-0.23	Hediger, W. (2006). Modeling GHG emissions and carbon sequestration in Swiss agriculture: An integrated economic approach. International Congress Series, 1293, 86–95.

Appendix 2

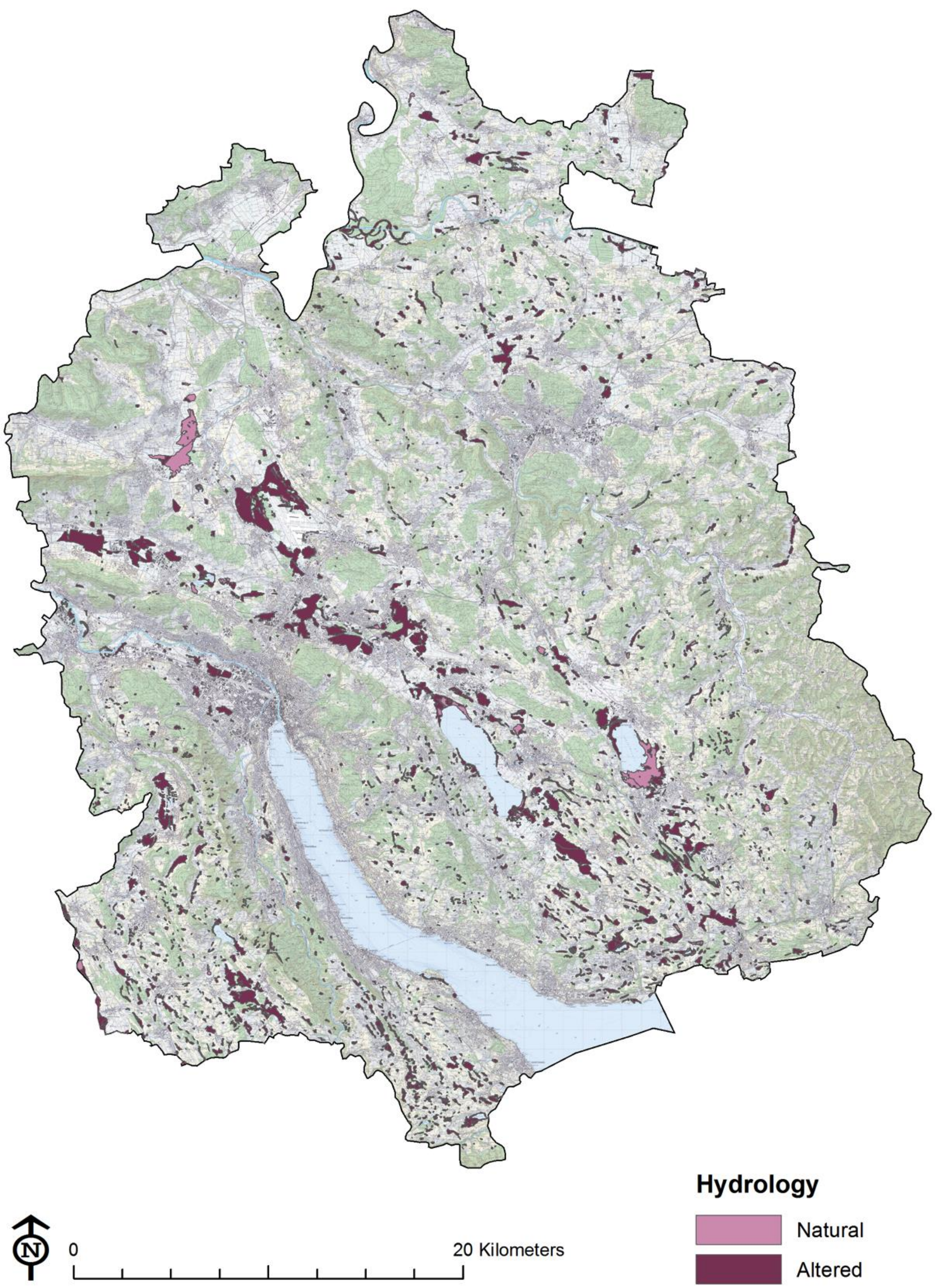
This table shows the results from the benchmarking exercise applied to the full range of uncertainty within the present emissions and restoration scenarios.

	CO2 Emissions – Low	CO2 Emissions – Mean	CO2 Emissions - High
Total Carbon Footprint	**15,719**	**19,649**	**23,579**
Annual emissions from passenger vehicles	3,309	4,137	4,964
Kilograms of coal burned	7,658,452	9,573,231	10,580,736
Propane cylinders for barbeque	654,958	818,708	10,043,458
Restoration of Protected Organic Wetlands	-5,947	-14,284	-18,693
Annual emissions from passenger vehicles	-1,252	-3,002	-3,935
Kg of coal burned	-2,897,436	-6,959,305	-9.107,413
Propane cylinders for barbeque	-247,792	-595,167	-778,975
Restoration of Organic Croplands	-3,365	-3,497	-7,539
Annual emissions from passenger vehicles	-708	-736	-1,587
Kg of coal burned	-1,639,461	-1,703,772	-3,673,074
Propane cylinders for barbeque	-140,208	-145,708	-314,125

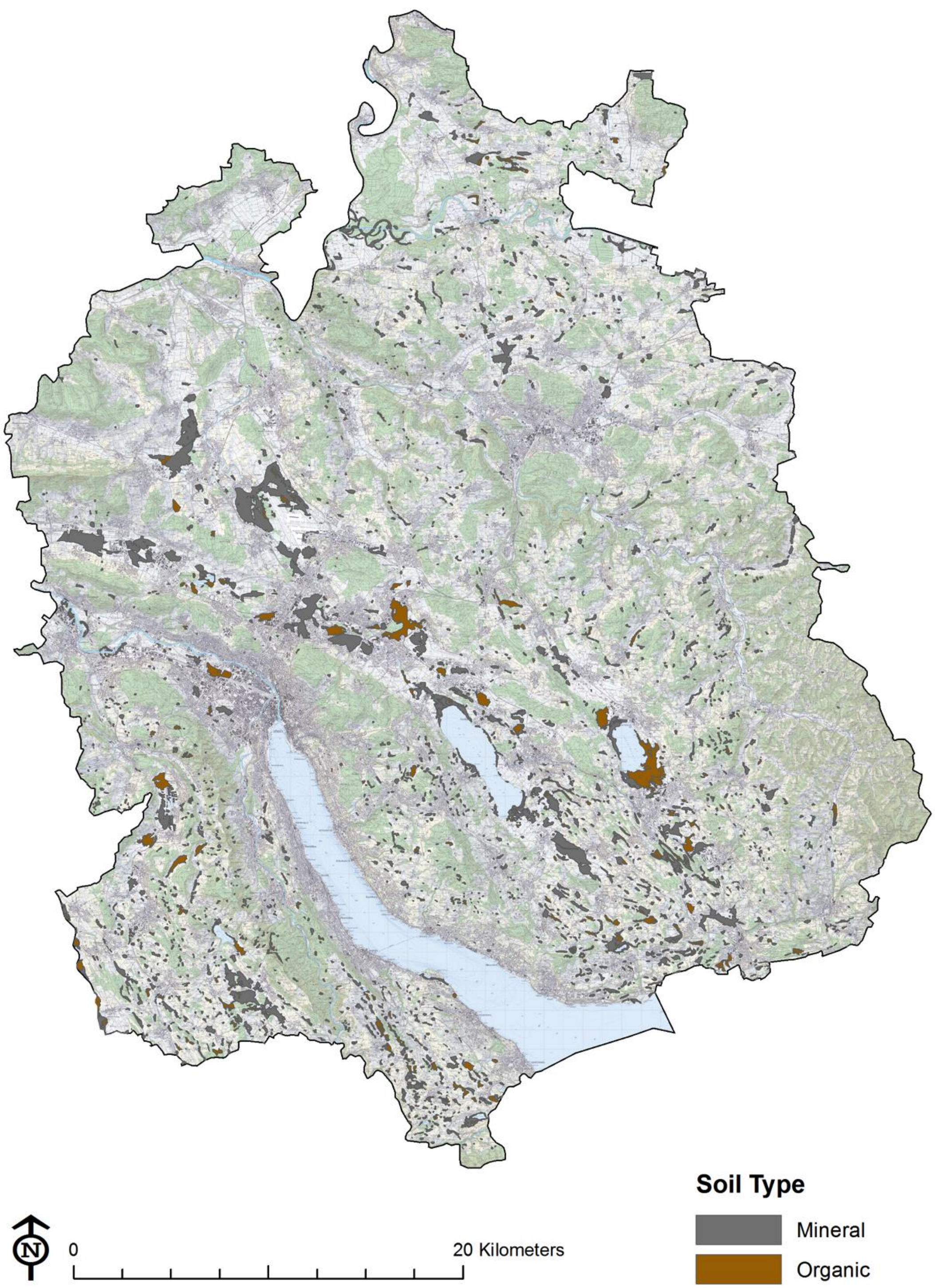
Appendix 3


Present Land Use: Kanton Zurich Wetlands
Present Land Use
Cropland
Forest
Wetland
Settlement
N
0
20 Kilometers

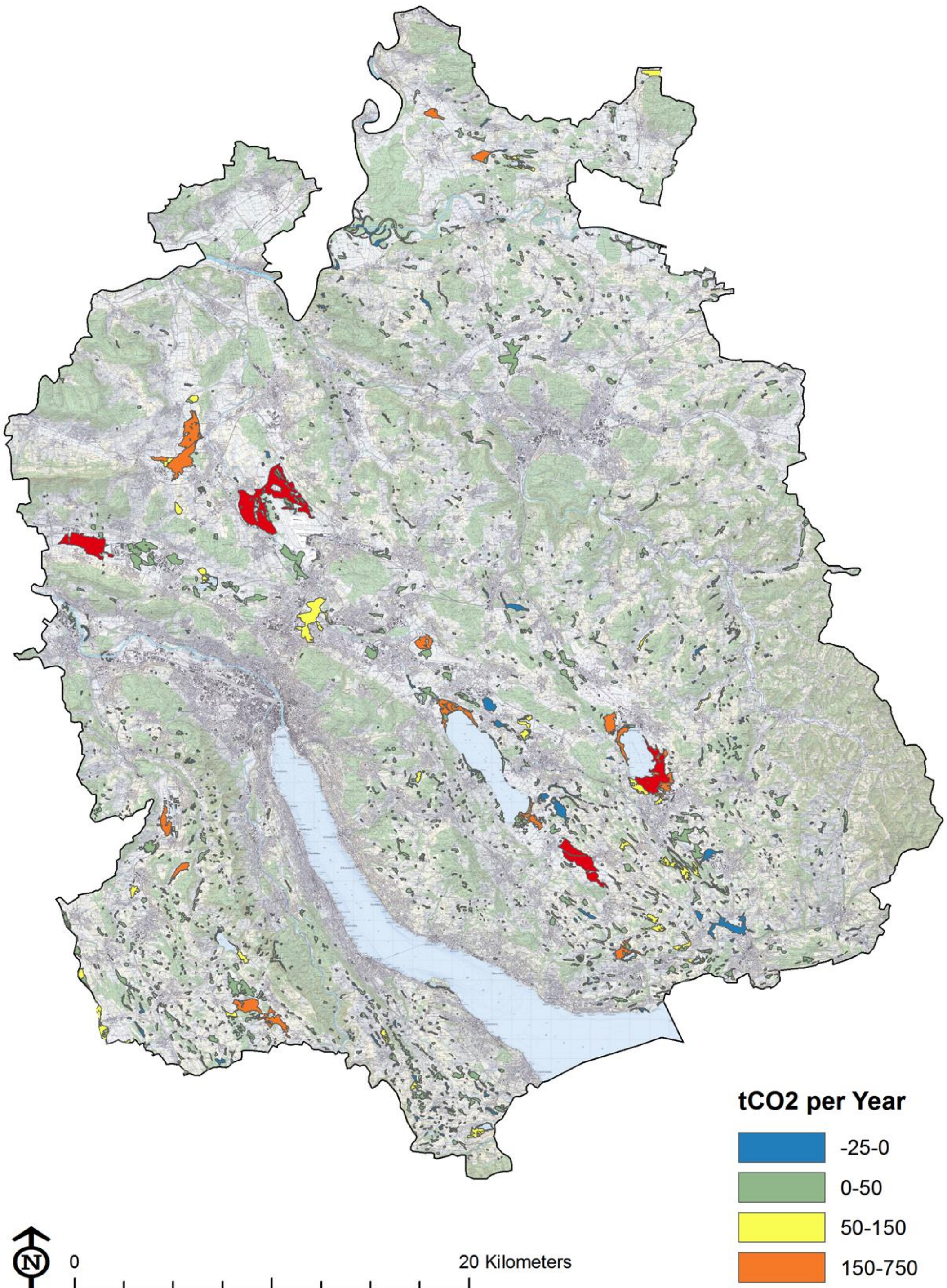
Hydrologic Conditions: Kanton Zurich Wetlands



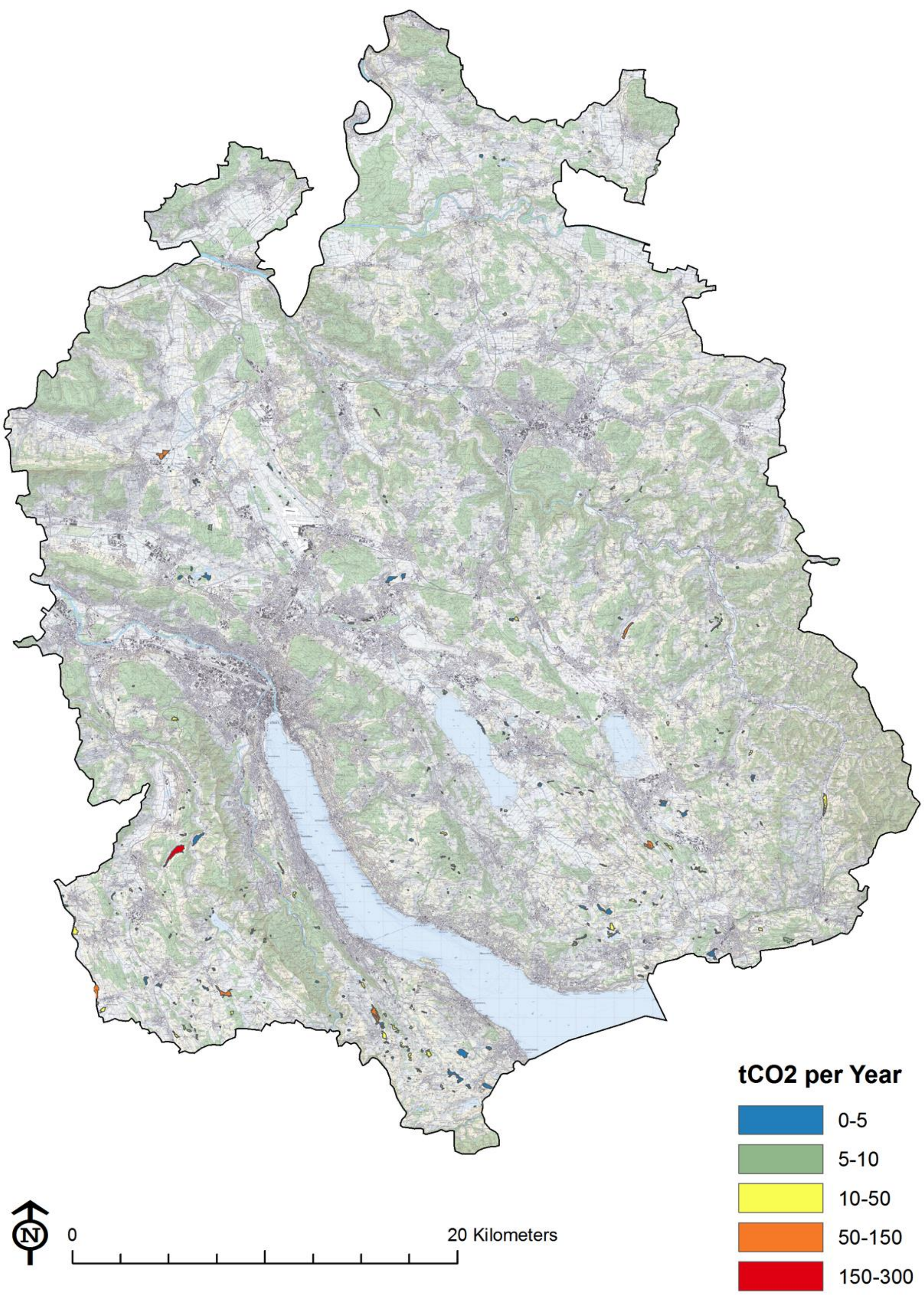
Soil Type: Kanton Zurich Wetlands



Carbon Footprint: Kanton Zurich Wetlands



Carbon Footprint: Priority Wetlands for Restoration



Carbon Footprint: Priority Croplands for Restoration