Ecological Economics 171 (2020) 106619

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Measurement and economic valuation of carbon sequestration in Nova Scotian wetlands

Kirsten Gallant[a], Patrick Withey[a,*], Dave Risk[b], G. Cornelis van Kooten[c], Lynsay Spafford[b,d]

[a] Department of Economics, St. Francis Xavier University, Antigonish, NS B2G 2W5, Canada
[b] Department of Earth Sciences, St. Francis Xavier University, Antigonish, NS B2G 2W5, Canada
[c] Department of Economics, University of Victoria, Victoria, BC V8P 5C2, Canada
[d] Department of Environmental Sciences, Memorial University, St. John's, NL A1C 5S7, Canada

ARTICLE INFO

Keywords:
Wetlands valuation
Carbon sequestration
Methane flux
Nova Scotia
Social cost of carbon

ABSTRACT

Carbon sequestration and methane flux in wetlands in Nova Scotia are measured. The social benefits associated with carbon storage are estimated using the net sequestration rate and estimates of the social cost of carbon from the Dynamic Integrated model of Climate and the Economy (DICE model). The net benefits of restoring wetlands in agricultural cropland are estimated based on these values and costs of restoration from the literature. The aim is to put a value on wetlands in Nova Scotia using original data rather than benefit transfers from other regions, thereby informing policy aimed at wetlands management in the region. Based on the results of this study, wetlands in Nova Scotia sequester 6.45 tCO_2eha^{-1} yr^{-1} on average, and release 1.46 tCO_2e ha^{-1} yr^{-1} as methane. The total benefits of carbon sequestration in wetlands in Nova Scotia are roughly \$124–\$373 ha^{-1} yr^{-1}, and range from \$5105 to \$39,795 ha^{-1} in total. The social benefit of wetlands in terms of carbon sequestration is as high as \$9.66 billion in Nova Scotia. Results indicate that protection of existing wetlands can be warranted on economic grounds. On average, it is not optimal to create wetlands for carbon sequestration, although it may be economically viable to target wetlands that are particularly productive in terms of storing CO_2. It may also be viable to restore wetlands if ecosystem services are considered along with carbon sequestration.

1. Introduction

Wetlands provide important ecosystem functions that have significant economic value, including the provision of ecosystem services (e.g., water filtration), non-market values (e.g., wildlife habitat), and the ability to store carbon dioxide (CO_2) and methane (CH_4). Decision-makers do not typically account for the value of ecosystem services provided by wetlands because markets currently do not exist. The benefits of retaining wetlands on private lands accrue to society and not the landowner, who usually has an incentive to convert wetlands to alternative land use (Heimlich et al., 1998). Roughly 80% of salt marshes along the Bay of Fundy and more than 50% of salt marshes in the province of Nova Scotia) have been lost, largely due to agricultural conversion and diking (Government of Nova Scotia, 2014).

The current study measures greenhouse gas emissions in Nova Scotia, Canada. It estimates the value of wetlands in terms of reduced CO_2 net of CH_4 emissions released (together measured in terms of CO_2-equivalence and denoted CO_2e). The goal is to better understand the value of wetlands in the region using original data. If policy makers in the region understand the value of wetlands for carbon sequestration, policy may be developed to manage wetlands in a way that captures their value and limits further wetland losses. The value of carbon sequestration can be measured using the price of CO_2e in jurisdictions that impose a price on carbon. Also, it can be estimated using the social cost of carbon from an integrated assessment model, such as Nobel Laureate William Nordhaus' Dynamic Integrated model of Climate and the Economy (DICE model). This study focuses specifically on the valuation of wetlands for carbon sequestration, but also conducts sensitivity analysis to include other ecosystem values of wetlands, based on values from the literature.

Much research has focused on the measurement of carbon sequestration in wetlands, as well as the valuation of wetlands in other jurisdictions. A large body of scientific literature has focused on the measurement of CO_2 and CH_4 in wetlands, much of which is reviewed in Mitsch et al. (2013). Research has also examined the economic value of wetlands, including meta-analyses that highlight the various

* Corresponding author.
E-mail address: pwithey@stfx.ca (P. Withey).

https://doi.org/10.1016/j.ecolecon.2020.106619
Received 19 August 2019; Received in revised form 25 January 2020; Accepted 30 January 2020
Available online 06 February 2020

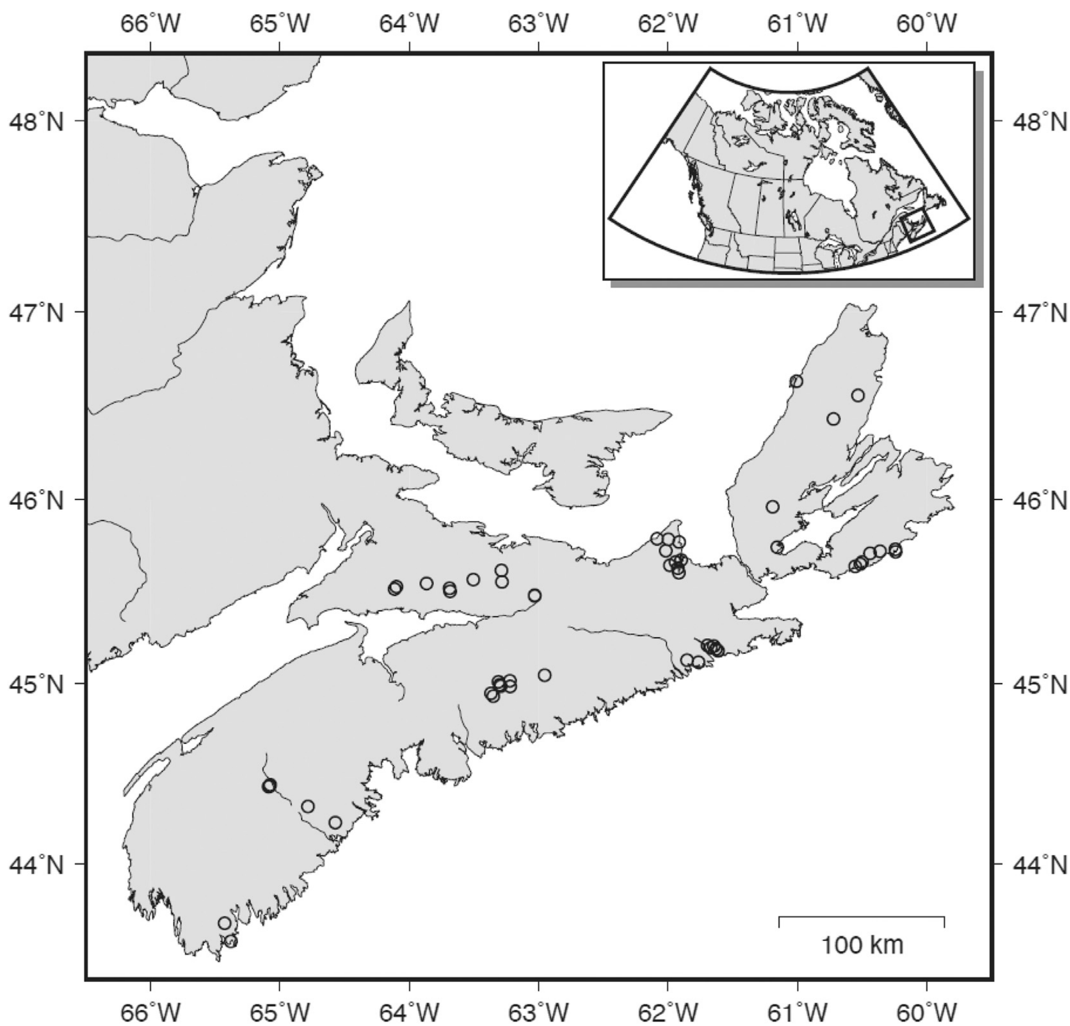

Figure 1: Sampled Wetlands in Nova Scotia

Fig. 1. Sampled wetlands in Nova Scotia.

methods used in valuing wetlands (Brander et al., 2006; Brouwer et al., 1999). An annual mean ecosystem value of wetlands of roughly US \$2800 ha^{-1} was estimated in Brander et al. (2006), but the annual median value was only \$150 ha^{-1}, which indicates that the distribution of values is skewed to the right with a long tail of high values. These values are the average for all global wetlands, although median wetland values in North America are higher at \$200 ha^{-1} than the global median value. These values do not include carbon sequestration values. Cortus et al. (2011) estimate an annual value of wetlands in Saskatchewan of roughly \$82 ha^{-1}, 41% of which can be attributed to carbon sequestration. Their analysis assumed a CO_2e price of \$10 per tonne of CO_2e (tCO_2e); using a higher price would result in a higher total value of wetlands, with a greater proportion of that value coming from carbon.

Several economic models have been used to evaluate the optimal provision of wetlands when non-market values are included. For example, van Kooten et al. (2011) and Withey and van Kooten (2011) evaluated how the optimal management of wetlands in Western Canada would change when their non-market value was taken into account. Further, Hansen (2009) estimated the potential profitability of restoring wetlands, specifically for the sale of carbon offsets. Profitability was based on the income and costs associated with the restoration process, where income included carbon sequestration rates and prices. In most cases, however, Hansen (2009) found that restoration costs exceeded the value of carbon, making wetlands restoration unprofitable.

Little work has been done in Nova Scotia to estimate the value of carbon sequestration in wetlands and the optimal provision of wetlands. Wetlands have been estimated to provide \$7.9 billion in ecosystem service benefits each year (Government of Nova Scotia, 2011). However, past research relied on benefit-transfer estimates from other regions to Nova Scotia. Further, most previous research did not consider whether wetlands turn into a net sink or a net source of CO_2e emissions if CH_4 emissions are included (Lal et al., 1995). Natural wetlands emit roughly 20–25% of global CH_4, and it is estimated that one quarter of the carbon they sequester is subsequently re-released as CH_4. The current study is the first to our knowledge to estimate the value of wetlands in terms of net CO_2e emission reductions in Nova Scotia. The carbon sequestration rate and flow of CH_4 are measured using sediment cores and static gas chambers, respectively. Stored emissions are valued using a variety of CO_2e prices estimated from the DICE model, and wetlands values are compared to the private costs of restoration to inform wetlands management policies in Nova Scotia.

2. Methods

The goal of this study is to measure and value carbon sequestration in wetlands in Nova Scotia. There are two distinct methodologies employed in this interdisciplinary study. In the first stage of the research, original data were collected on the net carbon sequestration rate from emissions sampling fieldwork across Nova Scotia. In the second stage, the value of CO_2e stored in wetlands is estimated along with the net benefits of restoring wetlands.

2.1. Emissions sampling

To measure total net sequestration in CO_2e terms, CH_4 flux is measured along with the long run carbon sequestration rate. The net sequestration rate is measured as the carbon sequestration rate (converted to CO_2) minus the methane released during the same time period (converted to CO_2e). In the remainder of the paper, CO_2e is used when referring to all emissions, including carbon sequestered in soils, or the sum of carbon in soils and methane released (the net sequestration rate). Data were collected from 55 wetlands across Nova Scotia during summer 2017. A geographic information system (GIS) analysis was used to establish criteria for the wetland sampling campaign, based on data obtained from the Government of Nova Scotia (2019), to choose a sample that includes different types of wetlands, and to capture variability in wetlands' ability to store GHGs in Nova Scotia.

This study sampled five different wetland types in Nova Scotia, including fens, bogs, swamps, and both fresh and salt-water marshes. It encompassed six different bedrock types (volcanic, gold-bearing, sulphide bearing, intrusive, evaporate, and organic) and eight vegetation types (tall shrub, aquatic vegetation, lichen, treed, exposed, graminoid, low shrub, and salt marsh). Further, it divided the province into eight regions to ensure a representative sample. Fig. 1 displays the wetlands sampled in Nova Scotia.

To measure CH_4 flux at the 55 chosen sites, we used 17-liter static chambers (Chmura et al., 2016) to collect gas samples, but with the addition of Styrofoam floatation platforms. Static floating chambers were used because they are low cost and can be used to take direct measurements of diffusive fluxes at the surface. Static chambers are useful when disclosing small-scale differences in gas flux (Xiao et al., 2016). We connected 10 m of 0.78 mm diameter tubing to the top of the chambers, which allowed the gas sample to be extracted from shore at the end of the measurement period.

Two static chamber measurements were made at each wetland. The static chambers were ventilated with atmospheric air before being deployed on the water surface for 15 min to allow the gases to accumulate, and samples were taken from the littoral zone. After 15 min, a 60 ml syringe was used to extract 420 ml of air from the chamber to clear out any atmospheric air lingering in the tubing. After clearing the air, a 20 ml sample was extracted and injected into a 12 ml vial, overpressurizing the vial for secure storage. This simple single-sample approach was sufficient for determining an approximate flux rate, and we confirmed that the 15-minute interval was well within the linear period of chamber concentration increase.

Air temperatures and water depth were recorded at each chamber. Collected gas samples were stored at 23 °C in the laboratory and analyzed within one month using a Varian GC420 gas chromatograph, equipped with CombiPal autosampler, and detectors for CO_2 (TCD) and CH_4 (FID). Calibration curves for lab analyses were built using traceable Matheson Tri-Gas standards appropriate to the range of observed sample concentrations.

Flux calculations (in umol m^{-2} d^{-1}, converted to tCO_2e ha^{-1} yr^{-1}) were made using the change in gas concentration within the chamber headspace over time from an assumed value of 400 ppm, using the Ideal Gas Law to account for differences in ambient temperature at the time of measurement. These values were then scaled to annual emissions. Even though we expect to observe differences in respired CH_4 diurnally, seasonally, and annually, for our purposes we assumed that measured "snapshot" values were generally representative over longer timescales. This a-temporal approach is similar to that of most other wetland studies.

To estimate long-run carbon sequestration rates, sediment samples were extracted from six of the 55 wetlands using a Piston Corer. A Piston Corer is designed for extracting saturated sediment without causing significant disturbance to the sample (Frew, 2014). This process involves putting a long heavy tube into the sediment over a fixed position and the "piston" within the tube acts as a vacuum to resist the movement of the samples (Kullenberg, 1947). The samples in this study ranged from 14 to 26 cm in depth. The samples were analyzed on a tray and separated and bagged into 1 cm increments. The samples were then dried and crushed by a mortar and pestle into a powder to be tested by an X-ray fluorescence (XRF) analyzer.

The amount of carbon sequestered at each wetland site was estimated as follows (Mahdavi et al., 2011):

$$C_c = C(\%) \times BD \times e \tag{1}$$

where Cc is the amount of carbon sequestered at a wetland site (g m^{-2}), C(%) represents the percent of total carbon in dry organic matter (approximately 50% carbon), BD is the bulk density of the sample, which delineates the dry weight of a known volume of soil (g cm^{-3}), and e symbolizes the thickness of the soil sample (cm).

To estimate the historical carbon sequestration rate, a soil accretion rate is estimated using traces of lead in the samples. The XRF analyzer identified ^{210}Pb activity in each 1 cm increment of soil. Since lead was phased out in the early 1990s due to regulations in the Canadian Environmental Protection Act, lead was used as a marker in determining the soil accretion, and thus carbon sequestration rate. It was assumed that the youngest traces of lead in dense concentration would be just less than 30 years of age. Therefore, the sample increment with the peak in ^{210}Pb activity is assumed to correspond with the 1990s.

The carbon sequestration rate (g m^{-2} yr^{-1}) was estimated based on how quickly the carbon accumulates over time, the depth of the sample, and the amount of carbon sequestered in the sample. The impacts of human disturbances are not taken into account and a constant annual accumulation rate is assumed.

Given a historical carbon sequestration rate and CH_4 flux at each site, all values are converted to tCO_2e per year and per hectare, and CH_4 (in CO_2e) released is compared to CO_2e sequestered to determine the net sequestration rate at each wetland. We also analyze wetland features (elevation, disturbance, vegetation and bedrock type) that impact GHG flux.

2.2. Wetlands valuation

The value of carbon sequestered in Nova Scotia (NS) wetlands is measured using the annual net sequestration rate, which is estimated using the methods in the previous section, and the price of CO_2e. The total benefit is measured as the sum of the discounted annual values over T years:

$$B = \sum_{t=1}^{T} \frac{P_{ct}}{(1+r)^t} G_t, \tag{2}$$

where B is the benefit (US\$ ha^{-1}), r is the monetary discount rate, G is the net tCO_2e stored in a hectare of wetlands per year, and P_c is the price of carbon (\$ per tCO_2e). Time periods of $T = 35$ years and $T = 85$ years were chosen. The first is consistent with the desire of the Inter-governmental Panel on Climate Change (IPCC) to reduce CO_2e emissions by 45% before 2030 and that countries must become carbon neutral by 2050 if the increase in global mean surface temperature is to be limited to 1.5 °C (IPCC, 2018). Thus, emissions in the next 35 years are particularly important. The second scenario is considered for sensitivity, and because wetlands sequestration may persist for a long period.

Data are required on the average net GHG stored per year in NS wetlands, variable G in (2), which is estimated using the methods described in the previous section. All emission values are converted to tCO_2e ha^{-1} yr^{-1} based on global warming potential (GWP). Since CO_2

is the reference gas, it is assigned a GWP of one, with the GWP potential of CH_4 taken to be 25 times that of carbon (EPA, 2017).

Data on the price of CO_2e are also required. Economists use Integrated Assessment Models to investigate the economic impact of projected climate change at a regional and global level. The most well-known model is the DICE model (Nordhaus, 2013),[1] which has been used to provide estimates of the value of the social cost of carbon (SCC). The SCC is the present value of all future damages caused by emitting one extra tCO_2e. Since the SCC captures the damages from emissions, its value is often used to inform the optimal carbon tax or price on CO_2e. Therefore, for our purposes, we use estimates of the SCC from the DICE model (version 2016R2-083017) to value fluxes in CO_2e related to wetlands policy in Nova Scotia.

One of the many parameters that the climate modeler needs to set is the equilibrium climate sensitivity (ECS), which is the expected increase in temperature from a doubling of the atmospheric concentration of CO_2 from 280 ppm by volume in pre-industrial times (circa 1750) to 560 ppm, while the early 2019 concentration is about 410 ppm. While earlier IPCC reports were much more assertive about the value of the ECS, stating a likely range of 2.0 °C to 4.5 °C with a best estimate of 3.0 °C, the 2014 Fifth Assessment Report (AR5) is much less certain about the ECS, reducing its lower bound to 1.5 °C and offering no best estimate (IPCC, 2013, 2014; Knutti et al., 2017).

The original version of the model employs an ECS value of 3.1 °C (Nordhaus, 2018), but, as a sensitivity analysis, we employ two other values. A value of 2.0 °C is used because recent studies suggest that the ECS value might be lower than 2.0 °C (Lewis and Curry, 2015, 2018; Mauritsen and Pincus, 2017; Schwartz, 2017). A higher value of 5.0 °C is also adopted as this value has been used in the DICE model to represent a climate feedback tipping point scenario (Lemoine and Traeger, 2016).

Finally, the net benefits of creating wetlands for CO_2e storage are estimated in Nova Scotia based on the costs and benefits of creating wetlands. The costs include the opportunity cost of moving land out of agricultural production. These values are taken from the literature, including Hansen (2009), and modified for the context of Nova Scotia. The benefits are the future value of the stream of CO_2e mitigated. The net benefits are estimated as

$$NB = \sum_{t=1}^{T} (P_{c_t} G_t - K_t)\frac{1}{(1+r)^t} \quad (3)$$

where all values are as above, r is the monetary discount rate and K_t are restoration costs, which include initial restoration costs plus foregone agricultural production.

3. Results

3.1. Emissions

Based on core samples taken in the summer of 2017, carbon sequestration in the six wetlands that were sampled in Nova Scotia ranged between 62.40 and 345.30 g C m^{-2} yr^{-1}, with an average rate of 176.53 g C m^{-2} yr^{-1}, or 647.20 g CO_2e m^{-2} yr^{-1}. The average soil accretion rate was 1.4 mm yr^{-1} and the average bulk density was 0.243 g cm^{-3}.

To estimate the climate impact of wetlands in Nova Scotia, we compare the average carbon sequestration rate (in CO_2e) to the average amount of CH_4 emissions released (flux) in CO_2e (as in Mitsch et al., 2013).

CH_4 fluxes were measured at the surface of 55 wetlands in the summer of 2017, including those wetlands where carbon sequestration was estimated. There were two separate samples at each site, and emissions were averaged across the 110 observations at 55 wetlands. CH_4 emissions averaged 0.016 g CH_4 m^{-2} day^{-1}. Assuming a GWP of 25:1 for CH_4 to CO_2, CH_4 emissions were multiplied by 25, and values were then expressed in CO_2e. The amount of methane emissions was therefore equal to 145.81 g CO_2e m^{-2} yr^{-1}. The maximum value was 2175.73 g CO_2e m^{-2} yr^{-1} and the minimum value was −43.88 g CO_2e m^{-2} yr^{-1}, where uptake of CH_4 was present similar to terrestrial forest soils locally (Lavoie et al., 2013).

The values estimated in this study are similar to those reported in the literature. The CH_4 flux values of 0.016 g CH_4 m^{-2} day^{-1} (or 4.37 g C m^{-2} yr^{-1}) are lower than those reported in Mitsch et al. (2013) for many wetlands in tropical regions (33–263 g C m^{-2} yr^{-1}) and Australia (12–22 g C m^{-2} yr^{-1}). However, the values found in this study are similar to those reported in Moore and Roulet (1995) for Canadian peatlands (less than 7.5 g C m^{-2} yr^{-1}). For carbon sequestration rates, Mitsch et al. (2013) report a broad range of 2–387 g C m^{-2} yr^{-1}. The results of this study (176.50 g C m^{-2} yr^{-1}) are within that range and similar to those in other studies for coastal regions of North America (Mitsch et al., 2013).

Since carbon sequestration averaged 647.10 g CO_2e m^{-2} yr^{-1} whereas CH_4 emissions averaged 145.81 g CO_2e m^{-2} yr^{-1}, wetlands in Nova Scotia can be considered carbon sinks, with total carbon sequestration of 501.29 g CO_2e m^{-2} yr^{-1} or 4.99 tCO_2e ha^{-1} yr^{-1}. These values are lower than Hansen (2009), who did not include CH_4 emissions, and can be used to estimate the value of wetlands per hectare and in aggregate in Nova Scotia.

3.2. Wetlands valuation

The value of carbon sequestration in wetlands in Nova Scotia is estimated as the price of CO_2e emissions (i.e., the SCC) multiplied by the net annual CO_2e storage of 4.99 CO_2e ha^{-1} yr^{-1} estimated in this study. The results from the DICE model are provided in Fig. 2 for forecasted periods from 2015 to 2100. When the ECS is 3.1 °C, the current value of the SCC is about \$45/tCO_2e (measured in 2018 U.S. dollars), rising to some \$130/tCO_2e by 2050. However, if the ECS is 2.0 °C, the current SCC is less than \$30/tCO_2e and its value in 2050 is about \$70/tCO_2e, and if the ECS value of 5.0 °C is used, the current SCC is about \$75/tCO_2e, with a value in 2050 of nearly \$265/tCO_2e. The values used in this study from the DICE model fall within the range of values considered using other Integrated Assessment Models (EPA, 2017), and our base case (ECS = 3.1 °C) is consistent with a \$50/tCO_2e. price of carbon for 2022 as adopted by the Government of Canada (2017).

Table 1 provides the estimated value resulting from the sequestration of carbon in wetlands, using the above approach. CO_2e values are multiplied by the SCC at the time they occur, and values are discounted to the present using a monetary discount rate of 2.5%.

Overall, for the parameters considered in this study, the value of wetlands for carbon sequestration in Nova Scotia varies between \$5105 ha^{-1} and \$39,975 ha^{-1}. The annual value of wetlands in 2015 is calculated as the annual emissions stored in wetlands (4.99 tCO_2e ha^{-1} yr^{-1}) multiplied by the value of the SCC for that year. Based on the highest SCC value (DICE model with ECS = 5 °C), the value of wetlands in 2015 is equal to \$373 ha^{-1} yr^{-1}. Aggregated until 2050 (T = 35) and 2100 (T = 85), the total values of wetlands are \$15,948 and \$39,975 ha^{-1}, respectively. Using the default ECS value of 3.1 °C, wetlands are valued at \$223 ha^{-1} yr^{-1} in 2015, with an aggregate wetland value by 2100 of \$22,738 ha^{-1}.

Nova Scotia has roughly 242,900 ha of wetlands (Government of Nova Scotia, 2018). The total annual value of carbon sequestration in wetlands in Nova Scotia can be calculated in a given year as the value per hectare multiplied by the hectares of wetlands in the region. In 2015, using the highest SCC value considered here, the largest annual value of wetlands is \$90.9 million. This value increases over time as the SCC rises, although it is much lower than the annual estimate of \$7.9

[1] It is open source, available at https://sites.google.com/site/williamdnordhaus/dice-rice.

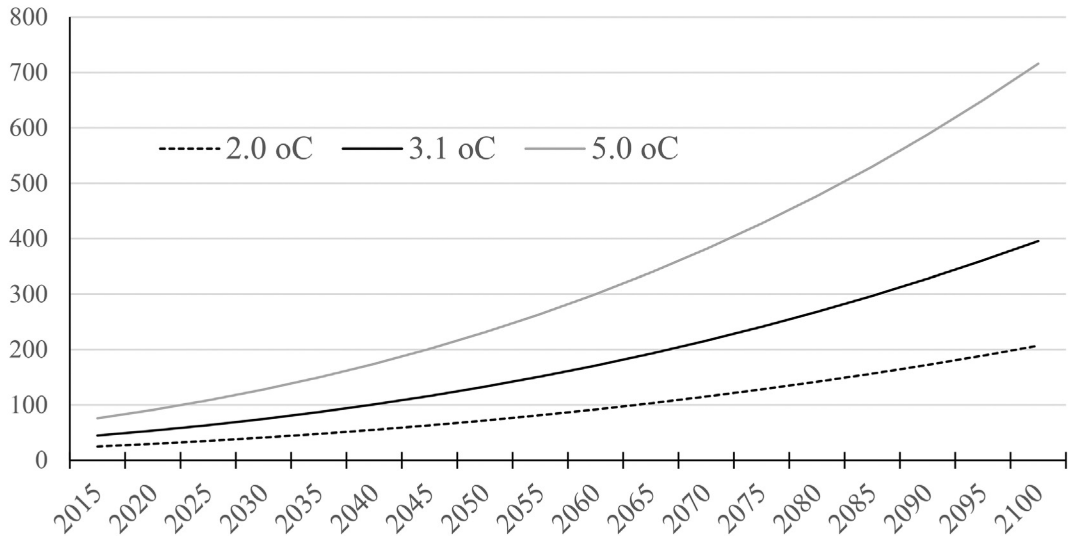

Fig. 2. Estimates of the social cost of carbon for three equilibrium climate sensitivity parameters, 2015–2100 ($US 2018).

Table 1
Value of wetlands (2018US$ha^{-1}) for various time horizons (T) and climate parameters (ECS), r = 2.5%.

ECS = 2 °C		ECS = 3.1 °C		ECS = 5.0 °C	
T = 35	T = 85	T = 35	T = 85	T = 35	T = 85
5105	12,244	9293	22,738	15,948	39,795

billion provided by Wilson (2000), who used a benefit transfer approach as opposed to relying on data gathered in Nova Scotia.

The estimates in the current study focus only on carbon sequestration, and are therefore underestimates of total wetlands values, although carbon sequestration likely accounts for a large portion of overall wetlands values (see Cortus et al., 2011; Belcher et al., 2001; Brander et al., 2006). Nonetheless, we calculate that the total aggregate discounted value of NS wetlands until 2100 might be as high as $9.66 billion. The value of wetlands is lower if other assumptions are used. Using the DICE model with ECS = 2 °C, the value of wetlands in 2015 is $124 ha^{-1} yr^{-1}, and the total aggregate benefit to 2100 is $12,244 ha^{-1}, or $2.97 billion for the entire province.

3.3. Wetlands costs

The costs of wetlands restoration include the restoration costs plus the forgone rents associated with alternative uses of the land (assumed here to be agricultural). The costs of restoration range from US $810–$5656 ha^{-1} in Hansen (2009), depending on wetland type, region and other factors. However, recent restoration projects in Nova Scotia cost between CAD$30,010 ha^{-1} and $100,038 ha^{-1} (Government of Nova Scotia, 2014).

The opportunity cost of using the land as wetlands, or the marginal value of an additional hectare of farmland in Nova Scotia, was estimated to be CAD$5518 ha^{-1}, which is the value of agricultural land and buildings in Nova Scotia (Statistics Canada, 2019).

We consider three costs when evaluating net benefits of wetlands restoration. In each case, we convert values to 2018US$ for consistency with the SCC estimates. This involves converting wetlands restoration costs in Nova Scotia and the opportunity cost of land from CAD$ to US $, and converting costs in Hansen (2009) and Government of Nova Scotia (2014) from 2007 and 2014 to 2018, respectively.[2] The first cost scenario, which we refer to as Hansen, uses a value of $8401 ha^{-1} that is based on the average value of the costs in Hansen (2009) plus the opportunity cost of land. The other two cost scenarios are based on costs in Nova Scotia; $29,158 ha^{-1} represents minimum costs for Nova Scotia, and $87,473 ha^{-1} represents maximum costs in Nova Scotia.

3.4. Net benefits of restoration

Table 2 presents the values of the net benefits of wetlands restoration in Nova Scotia, which are calculated by comparing the benefits of wetlands restoration for carbon sequestration (from Table 1) to the restoration costs discussed in the previous section. The net benefits of restoring wetlands for carbon sequestration vary substantially, from roughly $-82,000 to $31,000 per hectare, depending on restoration costs, time horizon and the value of the SCC. Positive net benefits values suggest that restoration can be supported if one assumes restoration costs equal to those in Hansen (2009), as well as the higher SCC values employed in the current study (with ECS equal to 3.1 °C or 5 °C). However, net benefit values are generally negative if one considers restoration costs in Nova Scotia, which indicates that restoration for carbon sequestration is not justified. We focus primarily on these scenarios, as data from Nova Scotia are the most relevant in the current context.

Using costs from the Government of Nova Scotia, wetlands restoration can only be supported if minimum restoration costs are assumed, and benefits are based on the highest SCC value and are assumed to persist for 85 years. In any other scenario, wetlands restoration will not be supported, including all scenarios using average restoration costs from Nova Scotia (a scenario that is not shown in Table 2). Clearly, if one uses restoration costs from Nova Scotia, wetlands restoration is economically inefficient from society's perspective. Further, net costs may be as high as $82,368 ha^{-1}. Restoration cannot generally be supported, even though we employ a much higher CO_2e price and a much longer horizon for wetlands benefits than Hansen (2009). This is due to slightly lower carbon sequestration rates in Nova Scotia, as well as much higher restoration costs.

The analysis above uses average carbon sequestration rates measured for wetlands in Nova Scotia. In theory, policy makers would

[2] The 2018 exchange rate comes from the Bank of Canada (https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/); the inflation calculate comes from the U.S. Bureau of Labor Statistics (https://data.bls.gov/cgi-bin/cpicalc.pl)

Table 2
Net benefits of restoration (2018US$ha^{-1}).

	ECS = 2 °C		ECS = 3.1 °C		ECS = 5 °C	
	T = 35	T = 85	T = 35	T = 85	T = 85	T = 85
Hansen	−3296	3843	892	14,337	7546	31,394
Min Cost	−24,053	−16,914	−19,864	−6420	−13,210	10,637
Max Cost	−82,368	−75,229	−78,180	−64,735	−71,526	−47,678

account for heterogeneity in carbon sequestration across wetlands, and target wetland types based on the amount of CO_2e removed from the atmosphere. However, emission fluxes in our sample do not vary in a systematic way. A number of site characteristics were recorded for each wetland, including the wetland and bedrock type, vegetation type, temperature, water depth, and wetland size. Based on univariate and multivariate regression models, none of the variables had a statistically significant impact on methane flux. A similar analysis was not conducted for carbon sequestration rates, given too few observations.

Given these results, we cannot inform policy that targets wetland types that generate higher benefits. Nonetheless, we consider the net benefits of restoration, assuming maximum sequestration values in our sample – policy makers will theoretically target those wetlands with the greatest sequestration potential. The maximum carbon sequestered annually is 345.3 g C m^{-2} or 12.63 tCO_2e ha^{-1}, and we assume no methane is released in this scenario. Under these conditions, and using the baseline SCC values from DICE with ECS = 3.1 °C, the discounted value of wetlands until 2100 is $57,520 ha^{-1}, compared to $22,738 ha^{-1} found in Table 1 for the same scenario. The net benefits of restoration would still be negative, assuming maximum NS restoration costs, or average restoration costs and a 35-year horizon. However, restoration can now be supported using minimum costs, or average restoration costs over an 85-year horizon. Thus, while restoration for carbon sequestration value cannot be supported for the average wetland in Nova Scotia, there will be some opportunities to restore wetlands in cases where wetlands sequester a lot of carbon and generate large benefits.

Finally, while restoration is not generally supported (based on the value of carbon sequestration) on economic grounds, draining existing wetlands cannot be justified either. The benefits from draining wetlands equal the value of agricultural land minus drainage costs. Another benefit of wetlands drainage is foregone nuisance costs for agricultural operations and benefits associated with the destruction of mosquito breeding habitat. However, these values are not included due to lack of information. Drainage costs in this region are roughly CAD$4942 ha^{-1} (Eastern Drainage Ltd., 2019). The value of agricultural land is CAD $5518 (see above). Therefore, the benefit of draining wetlands for the purpose of agricultural operations is roughly CAD$575 ha^{-1}, or a little more than US$400 ha^{-1}. The cost in terms of CO_2e released is much higher than US$400 ha^{-1} in all scenarios considered in this study; economic analysis suggests that current wetlands should not be drained.

4. Discussion and conclusions

The goal of this research was to collect carbon sequestration and methane emissions data for wetlands in Nova Scotia, and then employ CO_2e prices from the DICE model to estimate the overall economic value of carbon sequestration in wetlands in the region, thereby informing policy related to wetlands management. Wetland valuation has not been studied in detail in Eastern Canada, and the values generated in this study can provide decision makers with updated information specific to this region. The results can also provide an indication of the value of wetlands for carbon sequestration and storage in similar geographic locations.

The research is interdisciplinary in nature. The main results of this work are manifold, and are relevant to a variety of audiences. First, wetlands are found to sequester CO_2e emissions of roughly 6.45 tCO_2e ha^{-1} yr^{-1}, while releasing 1.46 tCO_2e ha^{-1} yr^{-1} from CH_4. This implies that wetlands in Nova Scotia are a net carbon sink, as CO_2e sequestered exceeds the CO_2e of CH_4 released. Further, the values found in this study are well within the range of values found in other studies that use similar methods to estimate CO_2e storage in wetlands. Second, wetlands can provide up to $9.66 billion worth of carbon sequestration value in Nova Scotia over the period 2015 to 2100. Overall, wetlands are determined to have an annual value between $124 and $373 ha^{-1}, and between $5105 and $39,795 ha^{-1} in total, depending on a variety of assumptions about the SCC and time horizon. Wetlands provide significant benefits, although values are lower than those cited by the Government of Nova Scotia (2011), which are based on valuation studies in other regions.

Our results also contribute to the economics literature on wetland values. Overall, our estimates of $124–373 ha^{-1} yr^{-1} are reasonable, considering that Brander et al. (2006) found median global ecosystem values of $150 ha^{-1} yr^{-1}, or $200 ha^{-1} yr^{-1} in North America (excluding carbon sequestration), and carbon sequestration is likely more valuable than other ecosystem services (Cortus et al., 2011), particularly if the higher SCC values are assumed. Finally, results indicate that, while wetlands provide significant benefits related to carbon sequestration, their restoration based on average carbon sequestration rates at average wetlands in Nova Scotia cannot be supported based on the potential income generated from storing carbon. However, opportunities may exist to restore wetlands if one targets only the most productive wetlands – those that sequester the most carbon.

Our results are also consistent with those of Hansen (2009), who conducted a similar analysis for the Prairie Pothole Region. Even though we use a much longer time horizon than Hansen (2009), and a much higher price for CO_2e (as determined by the SCC), wetlands restoration cannot be supported in most cases, due to the high costs of restoration in this region. This result is important for policy makers, as Nova Scotia currently uses a "no net loss" policy for wetlands. When wetlands are lost in one region, they must be replaced in another. While the carbon gains from restoring the wetlands are assumed to replace those lost when wetlands are destroyed, one cannot make an economic argument for such restoration based on carbon sequestration values due to high costs. However, destroying wetlands cannot be supported either; so, rather than replacing lost wetlands with new ones, an argument can be made for preserving existing wetlands. The results of this research also highlight the importance of using region-specific data to inform policy.

There are several caveats associated with this study and opportunities for future work. First, we did not estimate emissions over time or across seasons. We only estimated emissions in the spring of 2017. Second, emissions associated with newly created wetlands were not estimated, as all values come from established wetlands. Indeed, carbon sequestration in restored wetlands may differ from established wetlands. Based on Euliss et al. (2006), sequestration is expected to be higher in the initial years following wetlands restoration. Assuming that sequestration rates are 3.13 times higher than the long-run average in the first five years following restoration (adapted from Euliss et al., 2006), the value of wetlands (ECS = 3.1, T = 85) would be $25,182 ha^{-1} in Nova Scotia. This is not significantly different than the value for the same scenario considered in this study, and our policy implications remain unchanged. However, Moreno-Mateos et al. (2012) find that restored wetlands are less productive than established wetlands. In such a scenario, the net benefits estimated in this study would overestimate the value of restoration. This would not affect the long run value of carbon sequestration estimated at established wetlands in this study, nor would it impact the policy implications, given that wetlands restoration cannot generally be supported in Nova Scotia.

Third, wetlands provide other benefits besides carbon storage; these were not accounted for in this study. The median value of ecosystem services from wetlands in Brander et al. (2006) is \$150 ha^{-1} (or \$185 in \$2018US). If we assume ecosystem values of \$185 ha^{-1} yr^{-1}, then total wetland value in this study is \$36,252 ha^{-1} (assuming ECS = 3.1, T = 85). Again, our policy recommendations would be unchanged if we include median ecosystem benefits from Brander et al. (2006), say, and assume average restoration costs in Nova Scotia. There may be opportunities for restoration if we assume a higher SCC or ecosystem values (such as the mean value from Brander et al., 2006), but this result would not be robust. Finally, an avenue for future research would be to consider how human disturbance impacts carbon sequestration rates over time.

Acknowledgments

This research was supported by an Irving Undergraduate Student Research Mentorship Award (Frank McKenna Centre for Leadership, St. Francis Xavier University).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Belcher, K.C., Edwards, K., Gray, B., 2001. Ecological Fiscal Reform and Agricultural Landscapes, Analysis of Economic Instruments: Conservation Cover Incentive Program Background Paper. Ecological Fiscal Reform, National Roundtable on the Economy and Environment, Ottawa, ON.

Brander, L.M., Florax, R.J., Vermaat, J.E., 2006. The empirics of wetland valuation: a comprehensive summary and a meta-analysis of the literature. Environ. Resour. Econ. 33 (2), 223–250.

Brouwer, R., Langford, I.H., Bateman, I.J., Turner, R.K., 1999. A meta-analysis of wetland contingent valuation studies. Reg. Environ. Chang. 1 (1), 47–57.

Chmura, G.L., Kellman, L., Ardenne, L., van Guntenspergen, G.R., 2016. Greenhouse gas fluxes from salt marshes exposed to chronic nutrient enrichment. PLoS One 11, e0149937. https://doi.org/10.1371/journal.pone.0149937.

Cortus, G., Jeffrey, S., Untershultz, J., Boxall, P., 2011. The economics of wetland drainage and retention in Saskatchewan. Can. J. Agric. Econ. 59 (1), 109–126. https://doi.org/10.1111/j.1744-7976.2010.01193.x.

Eastern Drainage Ltd., 2019. Grow Your Crops and Business. Retrieved from. http://www.easterndrainage.ca/.

EPA. The Social Cost of Carbon. Retrieved July 27, 2017, from https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_. Html (2017).

Euliss, N.H., Gleason, R.A., Olness, A., McDougal, R.L., Murkin, H.R., Robarts, R.D., Bourbonniere, R.A., Warner, B.G., 2006. North American prairie wetlands are important non forested land based carbon storage sites. Sci. Total Environ. 361, 179–188.

Frew, C., 2014. Geomorphological Techniques, Chap. 4, Sec. 1.1. Retrieved from. https://geomorphology.org.uk/sites/default/files/geom_tech_chapters/4.1.1_Coring.pdf.

Government of Canada, 2017. Pricing carbon pollution in Canada: how it will work. Obtained online at. https://www.canada.ca/en/environment-climate-change/news/2017/05/pricing_carbon_pollutionincanadahowitwillwork.html.

Government of Nova Scotia, 2011. Nova Scotia Wetland Conservation Policy. Retrieved from. https://novascotia.ca/nse/wetland/docs/Nova.Scotia.Wetland.Conservation.Policy.pdf.

Government of Nova Scotia, 2014. Wetland Compensation. Retrieved from. http://www.novascotia.ca/nse/wetland/docs/Wetland_Compensation.pdf.

Government of Nova Scotia, 2018. Wetlands: Nature's Paradise. Retrieved from. https://novascotia.ca/natr/wildlife/conserva/nr-wetlands.asp.

Government of Nova Scotia, 2019. Wetlands Inventory. Retrieved from. https://novascotia.ca/natr/wildlife/habitats/wetlands.asp.

Hansen, L.T., 2009. The viability of creating wetlands for the sale of carbon offsets. J. Agric. Resour. Econ. 34 (2), 350–365.

Heimlich, R.E., Wiebe, K.D., Claassen, R., Gadsby, D.M., House, R.M., 1998. Wetlands and agriculture: Private interests and public benefits. In: Economic Research Service, September, Washington, DC (No. 1473-2016-120745).

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Cambridge University Press, Cambridge, UK.

IPCC, 2014. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK 1132pp.

IPCC, 2018. Summary for policymakers. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. World Meteorological Organization, Geneva, Switzerland 32 pp.

Knutti, R., Rugenstein, M.A.A., Hegerl, G.C., 2017. Beyond equilibrium climate sensitivity. Nat. Geosci. 10 (10), 727–736.

van Kooten, G.C., Withey, P., Wong, L., 2011. Bioeconomic modeling of wetlands and waterfowl in Western Canada: accounting for amenity values. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie 59 (2), 167–183.

Kullenberg, B., 1947. The Piston Core Sampler. Svenska Hydrografisk-Biologiska Kommissionens skrifter. Tredje Serien: Hydrografl, Band 1, Hafte 2.

Lal, R., Kimble, J., Levine, E., Stewart, B.A. (Eds.), 1995. Advances in Soil Science: Soils and Global Change. CRC Press, Boca Raton.

Lavoie, M., Kellman, L., Risk, D., 2013. The effects of clear-cutting on soil CO_2, CH_4, and N_2O flux, storage and concentration in two Atlantic temperate forests in Nova Scotia, Canada. For. Ecol. Manag. 304, 355–369. https://doi.org/10.1016/j.foreco.2013.05.016.

Lemoine, D., Traeger, C.P., 2016. Economics of tipping the climate dominoes. Nat. Clim. Chang. 6 (5), 514.

Lewis, N., Curry, J.A., 2015. The implications for climate sensitivity of AR5 forcing and heat uptake estimates. Clim. Dyn. 45, 1009–1023.

Lewis, N., Curry, J.A., 2018. The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity. J. Clim. 31, 6051–6071. https://doi.org/10.1175/JCLI-D-17-0667.1.

Mahdavi, M., Arzani, H., Mesdaghi, M., Mahdavi, K.H., Mahmodi, J., Alizadeh, M., 2011. Estimation of soil carbon sequestration rate in steppes (case study: Saveh Rudshur steppes). Journal of Rangeland Science 1 (3), 175–182.

Mauritsen, T., Pincus, R., 2017. Committed warming inferred from observations. Nat. Clim. Chang. 7, 652–655.

Mitsch, W.J., Bernal, B., Nahlik, A.M., Mander, Ü., Zhang, L., Anderson, C.J., Jørgensen, S.E., Brix, H., 2013. Wetlands, carbon, and climate change. Landsc. Ecol. 28 (4), 583–597.

Moore, T.R., Roulet, N.T., 1995. Methane emissions from Canadian peatlands. In: Lal, R., Kimble, J., Levine, E., Stewart, B.A. (Eds.), Advances in Soil Science: Soils and Global Change. CRC Press, Boca Raton, pp. 153–164.

Moreno-Mateos, D., Power, M.E., Comín, F.A., Yockteng, R., 2012. Structural and functional loss in restored wetland ecosystems. PLoS Biol. 10 (1), e1001247.

Nordhaus, W.D., 2013. Integrated economic and climate modeling. In: Dixon, P., Jorgenson, D. (Eds.), Chapter 16 in Handbook of Computable General Equilibrium Modeling, 1st edition. 1A. Elsevier, Dordrecht, NL, pp. 1069–1131.

Nordhaus, W.D., 2018. Projections and uncertainties about climate change in an era of minimal climate policies. Am. Econ. J. Econ. Pol. 10 (3), 333–360.

Schwartz, S.E., 2017. Heat capacity, time constant, and sensitivity of earth's climate system. J. Geophys. Res. 112 (D24), D24S05.

Statistics Canada, 2019. Value per Acre of Farmland and Buildings, at July 1—Agriculture Economic Statistics. Retrieved January 27, 2019, from. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210004701.

Wilson, S.J., 2000. The GPI Water Quality Accounts. GPI Atlantic Retrieved from. http://www.gpiatlantic.org/pdf/water/waterquality.pdf.

Withey, P., van Kooten, G.C., 2011. The effect of climate change on optimal wetlands and waterfowl management in Western Canada. Ecol. Econ. 70 (4), 798–805.

Xiao, S., Wang, C., Wilkinson, R.J., Liu, D., Zhang, C., Xu, W., ... Lei, D., 2016. Theoretical model for diffusive greenhouse gas fluxes estimation across water- air interfaces measured with the static floating chamber method. Atmospheric Environment 137, 45–52.