How to Reduce ‘Natural’ Methane Emissions to Mitigate Climate Change

A White Paper

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Context as of early 2022

The United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) says we have less than 10 years to meaningfully reverse course on increasing GHG emissions.[2] [3]

COP26 was a failure.[4] [5] [6] In particular, the attenuation-based ‘natural solutions’ hyped there by industry don’t take into account that the timeframe for real positive results now has less than a decade remaining. The necessary sense of urgency simply did not register at COP26.

The industrialized world is still tinkering with planning to have meetings to develop a plan to reduce CO_2 emissions in halting, incremental steps. Getting to stable CO_2 emissions on a global scale is still a pipe(line) dream, with no serious agreement in place, and not even a plan for penalties or serious enforcement. Everything we have tried to date – inaction, tinkering at the edges, study after study – has been a plan to fail, and as one would expect, it has failed. Even the shift to renewable energy has failed to keep up with the demand, and GHG emissions have increased in recent years due to increased generation from coal, natural gas and even oil-fueled plants.[7] As evidence of the impact on climate change, one need only refer to the increasing number of headlines covering climate-driven weather events: notably, warming at the poles; sea-level rise; floods; droughts; longer-lasting and more damaging storms…

In short, what we have done in the five decades since we knew that global warming / climate change was a real problem has all failed. Annual GHG emissions continue to rise. The GHGs in the atmosphere continue to increase. The planet is continuing to get warmer. The proposals on the table are not inspiring, or in many cases even likely to work. For a brief treatment of the current situation in Canada, see the circa COP26 posting in the Zer0 Carb0n brief.[8]

Nuclear fission is not a solution; it is a hydra of unsolved problems, and is already dying due to its own paradoxes. (The author worked in the nuclear energy sector. A chapter in his book *The Emperor’s New Hydrogen Economy* makes the case for abandoning nuclear fission, including ’small modular reactors’ (SMR), as a future energy path.)[9] Still, more taxpayer dollars are being spent to foster this technology.[10]

The much hyped ‘hydrogen economy’ is not a viable path forward. (There are a host of problems with implementing the hydrogen economy[11], but the ultimate killer is the magnitude of conversion losses in the energy cycle starting from green energy sources, creating far more waste heat than useful energy at point of use. So much so, that the hydrogen economy means we can’t get to GHG reductions within 50 years and meet anything like current demand for transportable energy.[12] [13])

Planetary geoengineering without scalability and an off-switch is unacceptable. It’s a hot-button issue on both sides of the flame war (not a polite debate). In earlier days, the discourse was a bit more civil, and in 2009 Ken Caldeira (now seen as a geoengineering proponent by many) was quoted as saying:
“Thinking of geoengineering as a substitute for emissions reduction is analogous to saying, ‘Now that I’ve got the seatbelts on, I can just take my hands off the wheel and turn around and talk to people in the back seat.’ It’s crazy.”[14]

For a reasonably balanced and digestible presentation of the state and reality of geoengineering as a solution to climate change, read Naomi Klein’s treatment of the topic in her book *This Changes Everything*.[15] After studying a number of climate geoengineering projects intended to mitigate climate change, Helen Muri of the Norwegian University of Science and Technology’s Industrial Ecology Programme says “we can’t rely on geoengineering to meet the goals of the Paris Agreement”.[16]

A significant, though decreasing, proportion of the world’s population has fallen for the disinformation campaign, and chooses to ignore data, evidence and weather reports, preferring to believe that climate change is not happening.

The image below is taken from *A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas*, Robert W. Howarth. [17]

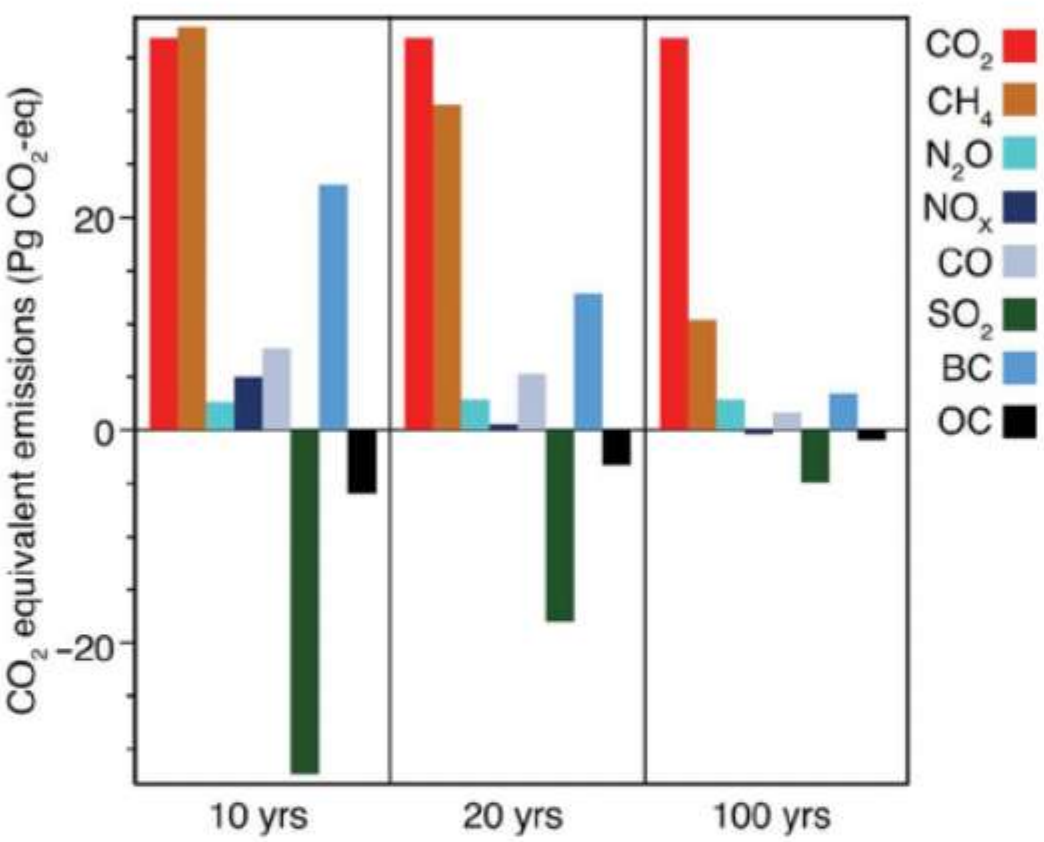


Figure 3. Current global greenhouse gas emissions, as estimated by the IPCC , weighted for three different global warming potentials and expressed as carbon dioxide equivalents. At the 10-year time frame, global methane emissions expressed as carbon dioxide equivalents actually exceed the carbon dioxide emissions.

Based on the above graph, in the time we have remaining to make a positive difference, **the biggest GHG warming culprit is not CO_2, it is CH_4 (aka natural gas or methane).**

Methane emissions, including industrial fugitive emissions, have been underreported for decades.[18] Some of that has been intentional.[19] [20] We are starting to gain a better grasp of the reality, since third parties used imaging technology which documented and quantified the emissions hazard.

> *Studies performed in Europe over the past[21] decade, and more recently in Canada, indicate that emissions from refinery and natural gas operations may be 10 to 20 times greater than the amount estimated using standard emission factors. – U.S. EPA[22]*

How to Reduce 'Natural' Methane Emissions to Mitigate Climate Change

Only in the last decade or two has it become practical for outsiders like the mainstream media to conduct surveys to search for methane leaks, let alone report them,[23] which is the first step towards corrective action.[24] [25] The next generation of methane-emissions tracking will likely be satellite-based, but it's not here yet;[26] we don't have the time to wait, and in many instances, we don't need to wait to act effectively.

While this paper presents a novel path for global GHG emissions reduction, it is not intended to replace any other viable approaches, such as tracking methane super-emitters using the TROPOMI satellite and shutting those emitters down.[27] We do need a true 'all-of-the above' approach, including shutting down industry fugitive emissions, starting yesterday.

We have viable paths to reduce our GHG emissions dramatically and quickly, if we choose to use them. While despair is understandable given the track record to date, it is misplaced if we choose a rational path. Sadly, as multi-national mega-corporations (notably the fossil-energy sectors) and governments in their thrall control the agenda, it is left to ordinary humans to do the extraordinary work necessary to allow our species to survive past another few decades. Economic growth is not inextricably linked to creating more GHG emissions.[28] Survival of the human species is irrevocably linked to reducing GHG emissions in the short term.

The world will have to take a few evidence-based actions in order to succeed. As denial and disinformation have been the program of the fossil-fuel sector and inaction has been the plan of governments for decades, these actions will be seen as a radical shift, like the 'polluter-pays' principle or the precautionary principle.

Even if governments met their newest 'ambitious' targets, it won't be enough to prevent catastrophe. This from the *UNEP Emissions Gap Report 2021*:

"The Emissions Gap Report 2021 shows that new national climate pledges combined with other mitigation measures put the world on track for a global temperature rise of 2.7°C by the end of the century. That is well above the goals of the Paris climate agreement and would lead to catastrophic changes in the Earth's Climate. To keep global warming below 1.5°C this century, the aspirational goal of the Paris Agreement, **the world needs to halve annual greenhouse emissions in the next eight years**"[29] (emphasis added).

Here is a short, incomplete list of what people can do to achieve what governments and mega-corporations and international 'free trade' agreements will not:

Switch from supporting organizations that are accelerating climate change to taxing them. End the use of fossil natural gas. End the use of coal. End the use of refined fossil petroleum products and the production of fossil crude oil. People can force these changes by their own choices. There are off-the-shelf substitutes for all those products now, many of which cost less than unsubsidized fossil fuels. These technologies have been known for decades but have not yet been taken up for substantial action to reduce CO_2 emissions from fossil-fuel use, largely because this requires breaking habits like continuing to subsidize fossil fuels, which means that the retail price is artificially depressed.

Stop using fossil fuels for heating, mechanical energy and propulsion. Start by accelerating the implementation of GHG-emissions taxes and use the funds to incent more measures to reduce emissions or even bring them below current levels with targets that have teeth, starting in 2022. The G7 and G20 agreed to such action in 2009, but to date (2022) not one nation in the G20 has actually implemented any such measure. Most continue to increase subsidies for fossil fuels, including the Canadian federal government via its ownership and construction of the Trans Mountain XL (TMX) pipeline ($21.4 billion per last estimate), which will increase the amount of fossil bitumen production, and in turn increase GHG emissions. ($21.4 billion would pay for half-a-million electric cars, or cover the current Canadian federal subsidy on almost 5 million zero-emissions vehicles.)

Reduce and even end our dependence on natural gas for heating and electricity generation, which is feasible, for reasons even beyond geopolitical dependence and climate-change impacts. Even more immediate issues include degradation of groundwater quality[30] and seismic disturbances[31] due to fracking and ground subsidence.[32] Implement programs to reduce fossil energy consumption (e.g., energy conservation in transportation and housing; switching from GHG-emitting energy sources to non-emitting sources, such as solar thermal, photovoltaics, wind, small-scale geothermal, small-scale hydro, biofuels…) and eliminate the financial and non-financial barriers to doing so (e.g. unnecessary pre-emptive energy audits paid for by consumers before work starts, and taxes on insulation, weather-sealing, air-source heat pumps and similar products which serve only to reduce energy consumption).

Where ground vehicles are still appropriate or necessary, shift to electric-drive systems, both grid-connected and battery-based. In the few cases where electric-drive technology is not yet at the stage required to fulfill all range and speed requirements, use biofuel or biofuel hybrid systems. Drop-in biofuels (bioethanol, biodiesel) and blends can bridge the remaining capacity gap until we reduce our dependence on long-haul transportation, and electric energy storage capacity improves.

Fossil natural gas is not a bridge fuel to lower GHG emissions. Biomethane has the advantage that it does not typically include significant quantities of benzene and hydrogen sulphide (carcinogens and toxins) compared with natural gas, and can be a net-zero GHG.

Massively shrinking fossil-fuel use is no small undertaking, but it is possible. The required technologies and approach have been known for decades (increased efficiency, conservation, reducing wasted energy, shifting to cleaner technologies). To date those have not made the desired impact on GHG emissions; we know this because global GHG emissions have continued to rise for the past few decades. However, as the costs of those renewable energy and storage technologies continue to fall with development and increasing scale of use, shrinking of fossil-fuel use is feasible. Electric drive appears to be yielding the most success in this regard, but ambitious targets do not equate to zero-emissions vehicles on the road in the desired numbers without mandates carrying real incentives and penalties. The uptake of electric vehicles in Norway, an oil-exporting nation, in the past 5 years makes clear how to achieve success.[33] But it is important to remember that the catastrophic climate change countdown clock is ticking.

Other than fugitive emissions from natural-gas production and transport, the above items focus primarily on CO_2. For the most part, climate-change mitigation has ignored the key GHG contributor in terms of global-warming impact: methane.

Methane

While the author has been calling out methane as the new GHG public enemy number one for some years now,[34] it has been largely ignored by industry, government and researchers. This is just beginning to change.[35]

Ever so slowly, the world is finally awakening to the fact that methane is the number one GHG. Perhaps it is not too late, but real action has not yet begun, and the track record is depressing.[36]

One of the few positive outcomes from COP26 was that at least lip service was paid to the methane issue, with the Biden administration seeking to set limits on industrial methane emissions.[37] Canada's response is to continue to focus on small measures to reduce CO_2 emissions, not to measure methane emissions effectively, and make more promises, always more promises.[38]

The U.S. approach is unlikely to succeed. The investments sunk in infrastructure which creates fugitive methane emissions (the oil and gas industry and major users of fossil natural gas for electricity generation, process heat, petrochemicals, fertilizers and more) will ensure enough inertia that the U.S.A. will not make significant progress within a decade. The targets – confined to a subset of industrial emissions – won't be ambitious enough to make the needed difference.

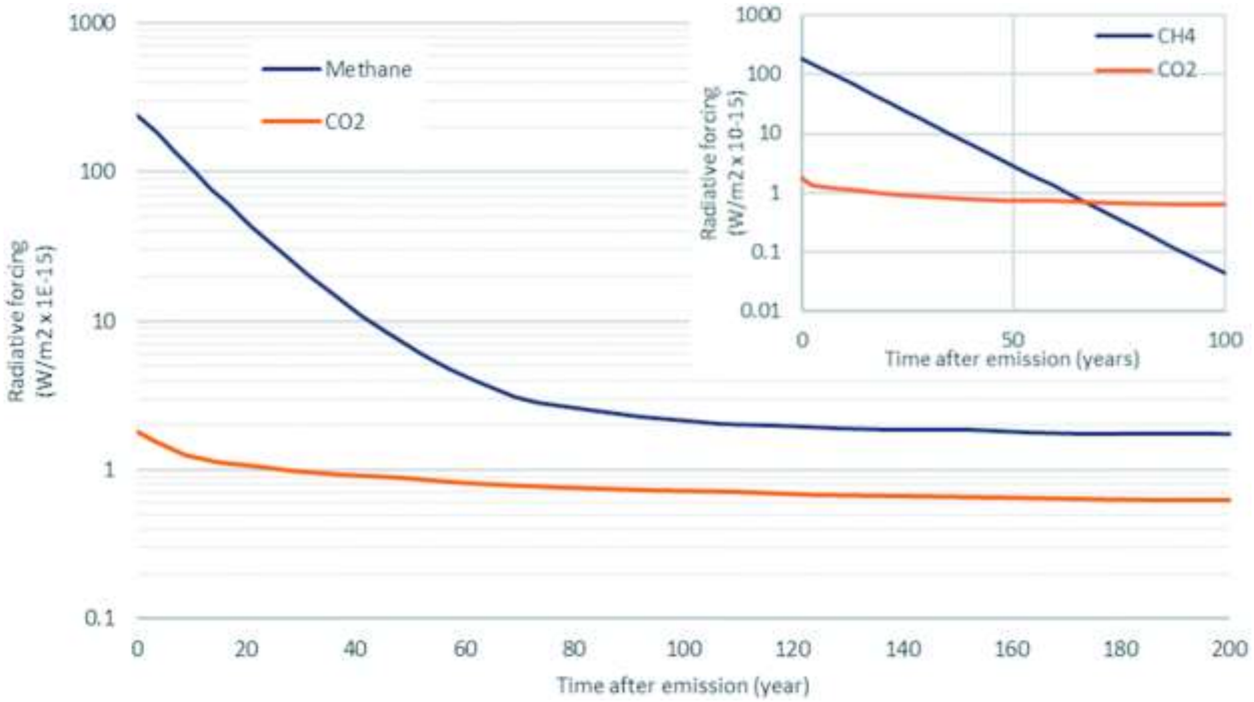
However, there is a significant source of global methane emissions other than industrial use and related fugitive emissions: anaerobic decomposition of 'natural' plant matter. The source of methane emissions does not matter; they will all increase the mean temperature of the planet because of radiative forcing, also known as the greenhouse effect. The IPCC says we have a decade to make a 180-degree turn on GHG emissions to avoid the worst of catastrophic climate change.

How to Reduce ‘Natural’ Methane Emissions to Mitigate Climate Change

It has been taken as an article of faith by the climate change mitigation lobby for decades that CO_2 is the key GHG requiring resolution, while CH_4 is a considerably lesser concern. Recognition of this myopia is becoming evident.

Weighting of the relative impacts of the different GHG emissions has been based on GWP_{100} numbers. This is not appropriate when we have imminent thresholds and tipping points facing us. GWP_{10} *has* to be the metric for decision-making, since the IPCC gives us no longer than 10 years to make a dramatic shift in order to avoid the worst of catastrophic climate change, and it’s already a problem. **The appropriate GWP number for methane** is not 28 (U.S. EPA GWP_{100} number[39]) or 56 (UN IPCC GWP_{20} number[40]); it **is 104** per the most recent UN IPCC figures [41] **or higher**[42]. (In the author’s opinion, it is absurd to use a 100-year timescale for measuring the impact of a compound with an average life of about a decade[43] in the atmosphere.)

The image below is from Methane emissions: choosing the right climate metric and time horizon (Balcombe, Speirs et al.)[44]



N.B. The above graphs present radiative-forcing values (*x* axis or vertical direction on the graph) using a log scale. It is a way to present exponential data compactly, but visually it diminishes the impact of the values on the extreme end of the curves. *The take-away here is that in 10 years the radiative-forcing effect of CO_2 is still very close to 1, while that of CH_4 is roughly 130. The IPCC’s number of 104 is conservative compared with more recent data.* **The critical new frontier for reducing planetary warming and catastrophic climate**

change is reducing methane emissions on a global scale, within the decade, and front-loaded as much as possible.

But how can we do that?

Opportunity

For the remainder of this paper, the **focus will be the reduction of methane production from 'natural' sources**, and describing an approach which can efficiently address the opportunity while providing a range of additional benefits.

The opportunity is to remove floating microalgal blooms and excessive aquatic plant growth (e.g. duckweed blooms) from water so that this biomass does not sink and decompose anaerobically, a massive source of methane.

Simply removing the excess biomass from the water surface has the potential to create a new waste-management issue. Fortunately, there are established uses for microalgae and other vegetative mass.

Uses for captured aquatic biomass (microalgal blooms and aquatic plants):

1) Biomethane – displacing fossil natural gas with a net-zero emissions drop-in substitute will reduce overall GHG emissions warming, and biodigesters are an established technology
(biomethane can be transported by means of the same infrastructure as is used now for fossil natural gas, including pipelines, and seasonal storage (Canada has roughly 1000 Bcf (billion cubic feet) of capacity– enough for 4 months' usage[45]) in compressed natural gas (CNG) containers and as liquified natural gas (LNG) for longer routes.) In terms of seasonality, biomass collected in early fall would decompose through the autumn and be available for winter space-heating demand.
2) Biodiesel – displacing fossil natural gas with a net-zero emissions drop-in substitute will reduce overall GHG emissions warming (biodiesel can be blended with petrodiesel for use in engines and as a heating fuel, using existing infrastructure).
3) Biolubricants – can displace petro-based lubricants with lower toxicity equivalents
4) Extraction of higher value organic components, such as carrageenan.
5) Compost – displacing petrochemical fertilizers with algal blooms, which are typically rich in the soil nutrients nitrogen and phosphorus, while providing many of the trace minerals needed to amend and maintain the soil health needed for growing healthy crops.

How to Reduce 'Natural' Methane Emissions to Mitigate Climate Change

Scale of the Opportunity

An existing and growing problem is plaguing many of our freshwater and nearshore bodies of seawater: algal blooms and floating masses of aquatic plants which reduce sunlight penetrating the water column. They foul drinking water and cooling-water intakes; and when they die off (annually in temperate climate zones), they sink to the water bottom to decompose anaerobically, producing methane which eventually floats out of the water and into the atmosphere as a potent GHG. During parts of the growth phase, algal blooms also reduce dissolved oxygen levels, which is harmful to marine life in the water body.[46]

Aerobic composting of the collected biomass will result in the production of carbon dioxide instead of methane[47]. As methane is a much more potent GHG than carbon dioxide, this is a huge win for efforts to mitigate future climate change.

For a sense of scale, this paper examines the Lake Erie algal bloom of 2011 because it was extensively reported on, monitored and measured, and because it seems likely to be repeated as global temperatures continue to rise and more agricultural run-off makes its way into the lake.

Lake Erie is far from the only 'eutrophic' body of water, a growing list of which includes a number of other major lakes in Canada, such as Lake Winnipeg, Lake Manitoba, Lake of the Woods, Killarney Lake and more. Eutrophic water bodies have an excess of nutrients or minerals which make them more prone to having excessive algae and aquatic plant growth, and reduced levels of dissolved oxygen, thus affecting non-plant life in the water.

Over half the lakes in Alberta are categorized as eutrophic or hypereutrophic.[48]

There are increasing reports of algal blooms in Nova Scotia and New Brunswick lakes. It's a longstanding problem in lakes in Quebec.

A presentation from Ontario shows the trend line (see slides 20-24; data end at 2010).[49] There is anecdotal evidence that this trend continues.

According to the government of Canada, "Many lakes across Canada have seen an increase in the occurrence of algal blooms."[50] The problem is likely to get worse, as temperate regions with lakes may follow the trend of New England (e.g. Lake Champlain, Finger Lakes region), which is warming faster than the global average.[51]

A report from Canadian Science Publishing identified the issue of the growing number of algal-bloom reports in 2015[52]. A 2021 report indicates that worldwide, the higher number of harmful algal blooms (HABs) reported is likely due to heightened awareness and testing/tracking capacity, rather than an actual significant increase in the number of HABs.[53]

How to Reduce 'Natural' Methane Emissions to Mitigate Climate Change

Canada has a large amount of the world's surface freshwater, but other countries are hardly immune from the problem. Lake Taihu in China, Lake Nieuwe Meer in The Netherlands, Isann's urban lakes in Thailand, etc. are also noted for perennial algal blooms.[54]

Calculations critical to the content of this paper are contained in the Appendix. The numbers produced there will be used in the following text.

Based on the numbers in Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions[55], the 2011 algal bloom event on the western end of Lake Erie covered over 5,000 square kilometres (roughly 2,000 square miles) at its peak, and was up to 10 cm (4 inches) thick.

By the author's calculations the 2011 Lake Erie algal bloom likely produced over 1.4 GT of methane. The amounts may vary by year, but this is a yearly event on Lake Erie. For comparison, Canada's targeted reduction in GHG emissions for 2030 from 2005 levels as of 2019 is 219 MT annual production[56] (730 MT[57] minus 511 MT, the 2030 target). Mitigating the effect of this single event, the difference between methane production and carbon dioxide production represents over 6 years' worth of that annual reduction target. Lake Erie is a perennial emitter of methane gas: "almost 500,000 metric tons CO_2-eq yr^{-1} total".[58] Finding that the bulk of Lake Erie's emissions emanate from the western basin aligns with the heavy weighting of the algal blooms in the same area.

Removing a fraction of this biomass to reduce methane emissions while offering other benefits provides the 'off-switch' for mass implementation of this solution. If a specific algal bloom were considered environmentally beneficial, it would not be collected.

There are multiple large lakes and innumerable small eutrophic lakes in Canada with perennial algal blooms, so the opportunity for expanding this quantity is immense.

Putting a Solution on the Water

A solution that addresses mobile pollution on the water surface has to meet the problem where it resides. It also has to be compatible with existing shore-based infrastructure for the handling of recovered materials. It has to be a capable work platform, able to flexibly carry crew and other personnel, equipment and materials safely and reliably on the water. It has to be sized to operate nimbly in shallow waters and make landings on beaches.

In short, it's a boat.

RESTCo has carried out some calculations based on performance of our proof-of-concept boat for the Ocean Saver* (OS), and we believe it can offer a financially competitive option for reducing GHG emissions compared with technologies being deployed today[59], while also offering other capabilities and advantages, in line with the current Canadian pricing on GHG emissions: C$50 per tonne CO_2e in 2022[60]. This figure is based on what was demonstrated in proof-of-concept testing, not projections based on scaled-up operation. The rate per tonne will likely drop dramatically if any of the scalability factors noted later are implemented, potentially into the range of $10 to $15 per tonne CO_2e avoided.

(* "Ocean Saver" is the working name for the boat which RESTCo has conceived. If it goes into production, it will likely be renamed for marketing and branding reasons.)

Using a boat has the advantage of allowing removal capacity to be shifted to areas of heaviest concentrations, or to protect specific features such as beaches, marinas, water intakes for municipal water supplies or cooling-water intakes for power plants, thus improving water quality in those waters. A trailerable boat can be moved from one water body to another if needs warrant.

Additional Benefits from Removal of Excess Marine Biomass

Removing excess microalgae and aquatic plants will also reduce the amount of nutrients and minerals present in the algae and plants[61] and may restore water quality as a wildlife habitat and source of drinking water. The quantity of microalgae and aquatic plants increases because excess nutrients, e.g. nitrogen and especially phosphorus, are available to them. These nutrients become part of the plant biomass and are therefore removed from the water body's excess nutrient inventory with the plant material. In lakes where nitrogen and phosphorus inputs have been reduced in recent years (e.g., use of low and no-phosphate detergents, reduced use of chemical fertilizer on lakeshore properties for cosmetic reasons), phosphorus-fed algal blooms can still be driven by inventories of phosphorus built up in the water body over a period of decades.

Eutrophication is exacerbated by several factors, the most important of which are the warming of the waters (planetary warming, injection of waste heat from the cooling of electricity generators and industrial processes) and continued run-off of agricultural chemical fertilizers. This increases the inventory of nitrogen and phosphorus in the water bodies, which drives the increased microalgae and marine plant growth out of balance and into a positive feedback loop, exacerbating the problem. We have known this for at least 50 years, and have made no effective changes to halt the progression of any of those three factors (planetary warming, waste heat injection into water bodies, increased inventories of chemical nutrients – notably phosphorus[62] – in water bodies). This increase in algae and aquatic weeds continues despite the fact that regulations have been introduced in past decades to dramatically reduce the introduction of new phosphorus (phosphates) into water bodies. Yet we still have perennial algal blooms, which suggests that phosphorus remains to drive their growth. It's time to do something different. The boat which removes excess microalgal blooms and aquatic growth in eutrophic waters, the treatment of the recovered biomass on land, and the sale of byproducts represent a comprehensive solution. It's also cost-effective in terms of GHG emissions reduction.[63]

One way of reducing the nutrient inventory in a body of water is to remove the excess floating biomass (algal blooms and drifting marine plants) that holds the nutrients, as proposed in this paper, to reduce methane emissions. Dried algae contain 4% phosphorus[64] and 2% nitrogen[65] by weight.

Reducing Nitrous Oxides in the Atmosphere

Nitrous oxides (N_2O & NO_X) combined will be the fourth-largest GHG emissions source over the next decade, based on the Howarth graph presented earlier in this paper.

One significant source of nitrogen compounds in water bodies is man-made chemical fertilizers. In addition to the direct impacts of nitrous oxides produced from man-made fertilizer, making this fertilizer is an energy-intensive process, which is typically powered by fossil carbon fuels, notably natural gas, which can also be associated with fugitive methane emissions. The production of ammonia as part of the Haber-Bosch process could account for 1-2% of worldwide carbon dioxide emissions.[66] Shifting to a compost rich in nitrogen and phosphorus as a fertilizer could reduce some of the GHG emissions associated with the ammonia-production process. Compost, having trace minerals in it, feeds the soil, which in turn feeds healthier plants. Compost mixed into the soil also increases water absorption and retention, providing some protection against run-off (which causes loss of nutrients like nitrogen and phosphorus because of heavy rains and spring melt; it also helps during periods of drought).

In the nitrogen cycle[67], nitrification and denitrification are the stages that produce nitrogen oxides (gaseous), which migrate to the atmosphere. These organic processes are enabled by marine plant life such as algae and aquatic weeds. Some of the nitrogen compounds also fall to the water bottom to create an inventory of nitrogen as a nutrient for future algae and marine plant growth.

When there is an algal bloom or floating weed mass, this indicates an excess of nitrogen (seawater) or phosphorus (freshwater), which is taken up in the plant matter and held there until the vegetation dies off and decomposes.

Removing the biomass while alive also removes the embedded nitrogen and phosphorus from the water body, and aerobic composting of the material changes the stages at which nitrification and denitrification occur.

How to Reduce 'Natural' Methane Emissions to Mitigate Climate Change

Additional Benefits from the Ocean Saver Multi-Role Boat

Boats typically have a home base and don't typically venture too far from it (community-based). There isn't always an algal bloom or seaweed mass to be cleaned up. At times when the Ocean Saver* (OS) boat is not removing undesirable biomass from the water surface, its tools can be used to perform other functions.

Plastic Waste Clean-up

Sadly, persistent plastic pollution is a growing problem in all the world's open waters. The quantities are significant, as indicated in clean-up projects along shorelines, such as on the shores of B.C.'s Discovery Islands[68]. Some shorelines are difficult to reach from roads, so a boat is not only an appropriate means to reach these areas, but also supports clean-up on the shoreline and collects floating pollution in nearshore waters. Where divers are tagging and removing sunken plastic pollution in the nearshore zone[69], competent dive-support boats need to be part of the solution.

When shipping containers that have come off ships because of storms[70] or running aground, or through mishandling in the loading terminal, break apart and the contents end up in the water or on the shore, this vessel can be used to pick up floating debris and pollution – be it liquid, semi-solid or solid on the water surface – or support onshore clean-up operations. Large blocks of packing foam, nurdles[71], and large plastic wrappings are commonly released during such events.

The OS boat can perform all these deployments. Liquids, semi-solids and small solids can be picked up by the gravity tower. Larger solids can be picked up by the trash gate, or pulled onto the deck and secured; if very large, they can be towed, likely to a nearby barge which will then be towed to a port for unloading.

Microplastics are a core problem, as they are easily ingested by small marine life and then are concentrated up the food chain to human consumption. Further, degrading plastic pollution, especially that exposed to sunlight – as on the water surface – emits GHGs such as methane, xylene and CO_2. As larger plastic pieces break into smaller pieces, off-gassing rates increase as the surface area to volume ratio increases. (The author is the recipient of a grant from the National Geographic Society to study tools to remove microplastic pollution from open waters.) Despite very recent interest in addressing the problem of microplastics, most technologies deployed to date cannot pick up microplastics, and none are able to deal with microplastic pollution already in open water. The OS boat with the gravity tower can.

(RESTCo maintains web pages related to plastic-waste science and media items, as well as suggestions for viable solutions.[72])

How to Reduce ‘Natural’ Methane Emissions to Mitigate Climate Change

Spilled-oil Recovery

In models and test-tank demonstrations, the technologies proposed for the collection of excess floating biomass semi-solids have shown they can also be used to recover spilled crude oil or refined hydrocarbon products. While spilled hydrocarbons definitely have a negative impact on GHG emissions, the more immediate hazards of oil spills make a stronger financial case for removing the spilled fluids as quickly as is practicable, and rapid response is critical as the spilled fluids spread across the water surface quickly. With time, spilled oil will break down into a range of GHGs, including carbon dioxide, methane, and nitrous oxides.

Rapid response (based on local availability of boats capable of highly effective spilled-oil recovery) will also reduce the amount of oil which reaches the shoreline, where it is more expensive to clean up.

With the removal of algal blooms, excess floating aquatic weeds, spilled oil and refined oil products and floating pollution of all kinds, overall water quality will be improved.

Emergency Response

Because this vessel is designed to be trailered and to operate with very shallow draft, it could be used in flooded areas to move people, material and equipment. As climate change causes more flooding events and disrupts infrastructure like roads and bridges[73], this boat could make a small but significant contribution. Once emergency response has shifted to restoring basic functions, the pump from the boat could be used to pump water out of sand-bagged areas and basements. If hydrocarbons or particulates are present, the filtering function of the boat could be used in conjunction with the pump to remove contaminants.

Scalability of the Solution

Larger Collection Cross Section

Employing bow sweeps to create a swept area of 4 metres instead of 0.6 metres as was done in the proof-of-concept testing would increase the collection rate by a factor of more than 6.

Operating Hours per Day

Our current algae-removal scenario assumes 4 hours per day of collection operation. This could easily be increased by a number of measures including:

- Reducing the time in transit from shore to work area by using floating storage or transfer to a support barge or other vessels of opportunity
- Extending the shift length of crew (algal blooms tend to occur where there are extended daylight hours)
- Exchanging crews on the water or at a landing site

- Fitting out the boats for night-time operation

Number of Vessels

Putting a number of vessels to work in a specific algae-removal zone or to respond to another type of environmental event will increase the amount of material which can be removed in a given time in proportion to the number of vessels. This is likely critical in events like oil spills where the oil spreads quickly, and frequently concentrates in areas of higher density (streamers) which can be approached as multiple simultaneous operations.

Vessel Size

A larger vessel will increase the amount of material that can be collected in a given time, will be less constrained by access to shore support on a frequent basis, and can carry more recovered material. Such a vessel might be appropriate for collecting floating pollution in ocean gyres.

Conclusion

Climate change is the defining issue of our time, and is an existential crisis for our species, as well as some other life-forms currently co-habiting with us on Earth. Even with five decades’ warning, we have failed to meaningfully address the problem, and we continue moving in the wrong direction. Methane is the key driver of radiative forcing, which is warming the planet. One key source of methane production – exacerbated by anthropogenic activities (heating of eutrophic waters, adding excess nutrients to water bodies on an industrial scale) – is the anaerobic decomposition of algal blooms and other floating aquatic biomass. Removing this excess floating vegetation and composting it aerobically, or otherwise converting the produced methane into carbon dioxide, will reduce the massive global-warming contribution to a level that could prevent our reaching 1.5°C above pre-industrial levels before the end of this decade. A multi-purpose boat is posited as the key piece of a cost-competitive solution.

Appendix – The Math

GHG Production from Anaerobic Decomposition of Marine Biomass

How much methane is actually produced from the anaerobic decomposition of a litre or kg of algal bloom or other floating biomass?

'Wet biomass' mentioned here is drained but not dried material, as would be used in a biodigester.

The methane-production numbers for marine biomass are taken from *Biochemical methane potential of biomass and waste feedstocks* [74] (D.P. Chynoweth, C.E. Turick, J.M. Owens, D.E. Jerger and M.W. Peck). See Table 7, 'Miscellaneous Feedstocks'; the line for microalgae shows 0.183 litres of methane per gram of wet microalgae.

Where other material is mixed with the microalgae, the value for methane per gram of biomass is typically higher – the value for all seaweeds (Table 12) is actually shown as 0.26 -0.40 liters of methane per gram of biomass. For this paper, we use the lowest value – for microalgae): 0.183 litres of methane per gram.

Baseline data in the 2020 report *Improved Algal Sludge Methane Production and Dewaterability by Zerovalent Iron-Assisted Fermentation* (Shixong Geng, Kang Song, Lu Li and Faxhi Xie) are in a similar range for algae.

Based on the paper by Chynoweth et al, methane production is conservatively estimated as 0.183 litres of methane gas (STP) per gram of mixed organic matter (volatile solids) for various marine plants (ranges from 0.25 to 0.41 litres per gram) and microalgae (0.183). At a more intuitive scale, that is 183 litres per kg.

Molar mass of CH_4 = 16.04246 g/mol (https://www.convertunits.com/molarmass/CH4). A mole of methane at STP occupies 22.4 litres (http://nobel.scas.bcit.ca/chem0010/unit7/mole8.htm). The mass of methane gas per litre (STP) is 16.04246 grams per mole / 22.4 litres per mole) = 0.71618125 grams per litre.

Therefore, the mass of methane produced from anaerobic composting of 1 gram of microalgae is (0.183 litres of methane per gram of microalgae × 0.71618125 grams per litre of methane) = 0.13106116875 grams of methane output per gram of wet microalgae input.

Shifting units to more relatable kilograms and rounding down for convenience, 131 grams of methane will be produced from the anaerobic decomposition of 1 kilogram of wet microalgae.

104 is the methane GWP_{10} multiplier per IPCC (2018)[75] (see page 39). This is a conservative figure; subsequent publications put the figure at 120 or higher.

Using 104 as the GWP_{10} value for methane, the CO_2e advantage per kg of microalgae (or mixed) biomass will be 103 × 0.131 grams **or 13.493 kg CO_2e per kg of wet marine biomass** removed from the water surface, rounded down to 13 kg CO_2e for subsequent calculations.

13 kg CO_2e per kg of methane avoided per kg of microalgae decomposed aerobically instead of anaerobically is equivalent to 13 tonnes CO_2e avoided per tonne of removed microalgal biomass and decomposed aerobically (e.g. composted).

Calculations from the 2011 Lake Erie Algal Bloom Event

Maximum event area covered: 5,000 km^2
Measured depth near event centre: 10 cm
Assumption: average depth of algae would be 5 cm, but 4 cm (0.04 m) will be used in order to be conservative. An ‘inverted alluvial deposit’ slope is assumed to arrive at an average thickness of 5 cm, and is then reduced by 20% to be more conservative.
Assumption: effective, early response to remove bloom would reduce the effective maximum coverage area to 3,000 km^2 or 3,000,000,000 $m^2$3,000,000,000 m^2 × 0.04 m = 120,000,000 m^3
1 m^3 of wet biomass taken from the water surface (barely buoyant – about 0.95 kg/litre) weighs about 950 kg or 0.95 tonnes
120,000,000 m^3 of wet microalgae weighs about 114,000,000 tonnes.
Based on the figure of 13 tonnes CO_2e avoided (calculated above) per tonne of wet microalgae removed and composted, 114,000,000 tonnes of microalgae would be equivalent to 1,482,000,000 tonnes CO_2e avoided (almost 1.5 billion tonnes).

Estimated Cost of Algal-Bloom Collection and Avoided GHG Production

The specific gravity of wet freshwater algal bloom is about 0.95, which makes it buoyant. This is why the patented gravity separation skimmer is effective at picking up floating aquatic weeds and floating algae. This was demonstrated by RESTCo in 2019. RESTCo has also developed a unique conveyor collection unit which can pick up microalgae and microplastics (as well as larger floating items) while allowing water to drain off. This device was demonstrated in 2020.

The limiting factor for boat collection capability is the encounter rate (skimmer intake width × forward rate × biomass depth). The effective width of the boat can be increased by using bow sweeps, which presents a wider opening for funneling material to the boat’s collection channel (gravity separation tower or conveyor collector).

Based on our testing, the proof-of-concept devices can collect at least 600 kg of wet biomass per hour on a small boat (5 metres LOA), most likely more. To be conservative, we use 600 kg of wet biomass per hour (drained but not dried). This testing was done using only a 0.6-metre opening, with no bow sweeps employed. With sweeps, the effective collection (swept) width could easily be 4 metres.

How to Reduce ‘Natural’ Methane Emissions to Mitigate Climate Change

We assume that a single small boat, working alone, can collect effectively for 4 hours per day, allowing time for transit to and from the collection zone, off-loading collected material at shore, and providing breaks for crew. A number of measures could increase this period, such as using support boats to transport the collected material to shore, bringing out replacement crew, extending the operating day for crew beyond 8 hours. We see 4 hours’ collection time per day as very conservative.

4 hours of active collection per day will prevent 31 tonnes of CO_2e of emissions (2400 kg × 13 kg CO_2e per kg of wet marine biomass = 31,200 kg CO_2e, or 31 tonnes, rounded down)

As the objective of the exercise is to reduce GHG emissions, an electric-drive system is assumed. Such drives are becoming commercially available as of 2020, and the expectation is that a 7-metre boat will operate in the nearshore zone close to a home base. A portable internal combustion generator running on net-zero renewable biofuels (biodiesel, ethanol – likely E85, or biopropane) could be provided as a range-extension option.

Based on calculations and assumptions stated below, daily operating cost would be about C$1,500. Spread over 31 tonnes CO_2e, the overall operating cost, using this vessel and local support infrastructure, is about C$50 per tonne CO_2e emissions avoided.

Financial Calculation Assumptions – Lifetime Boat Operating Costs

Interest costs and net present value are ignored for this estimate.

No advance revenue from carbon credits or use of harvested material is assumed.

Based on initial boatbuilders’ estimates, C$240,000 per boat as completely fitted-out cost, including second battery at boat half-life and taxes.

A 20-year life span results in straight-line amortization of C$12,000 per year. (capital cost allowance for taxes can be disregarded in this instance, but likely could be written off in about 3 years for the purchaser.)

100 operating days per year comes to $120 per operating day (in other applications the boat may operate for more than 100 days per year, and depending on length of open-water operating season – which is getting longer due to planetary warming. Some areas with algal blooms have open water year-round).

Amortization – $120 per day

Labour – $600 for crew of 2 per day (loaded cost, 2022 wage rates, 6-hour day (four hours’ active collection)

Fuel – $12 per day (80 kWh)

Total: $732 per day

Gross estimate of 100% net overhead for barges, towing, dock use, offloading from barges, bladders or other locally available containers to ground haulage (dump trucks), all contracted locally, including their labour components. This assumes that land near the shoreline is too valuable to be used as a composting space.

Daily cost with 100% overhead: \$1464 or approx. \$1500 (rounded up).

\$1500 per operating day / 31 tonnes CO_2e = approximately \$50 per tonne CO_2e avoided.

Reference Prices for GHG Credits

Comparing that with US\$30 in 2017 for best-cost approach to CO_2 avoidance or capture,[76] which is onshore wind generation (see Chart 1[77])

Two conversions required: inflation indexing from (January) 2017 to 2021[78] and currency conversion

U.S. CPI (1982 base) in January 2017 = 236.854
U.S. CPI (1982 base) in January 2021 = 255.296
Doing the division, about 8% overall inflation in the 4 years.

US\$30 (cost per tonne CO_2e (Gillingham & Stock)) in 2017 is equivalent to US\$32.30 in 2021.

Currency conversion – use \$0.80 (close to 2022.03.31 rate)

\$32.30/0.80 = C\$40.375

For 2022, the Canadian government's assumed value of a credit for 1 tonne of CO_2e is \$50.

By comparison, our estimated cost per tonne CO_2e avoided emissions is \$11, or about 20% of the Canadian government's assumed GHG price (2022). (Based on scaling up the swept cross-section compared to our proof-of-concept demonstration using a 0.6 metre opening.)

Composting process is expected to take less than a year, so in seasonal zones, the same land space for composting could be utilized year after year.

GHG emissions reduction credits are not universal, and it will take time to establish higher value downstream uses than composting. However, if GHG credits are available, it's possible that they could cover the full cost of operating these boats, with funds remaining to reinvest in expansion.

Nitrogen and Phosphorus Content of Algae

Note: the numbers here are for dry mass of algae, while most other calculations for algae in this document are for drained wet biomass.

How much phosphorus is in algae?

https://link.springer.com/article/10.1007/s10201-018-0562-2

"Total P (TP) in algae biomass ranged from 2671 to 5385 mg kg^{-1} of dry matter."

Average 4028 (2671 + 5385)/2, rounded to 4,000 mg = 4 grams kg^{-1} = 100 grams

4 grams / 100 grams = 4% of algae (dry matter) is phosphorus.

How much nitrogen is in algae?

https://energypedia.info/wiki/Nitrogen-content_and_C/N-ratio_of_Organic_Substrates

From the table, algae are shown as containing 1.9% nitrogen; round to 2% for ease of calculations.

How to Reduce ‘Natural’ Methane Emissions to Mitigate Climate Change

Glossary

Term	Definition
BC	Black carbon (e.g. soot)
Carbon dioxide	The most common greenhouse gas (GHG), produced by the oxidation of carbon, notably by burning carbon fuels such as wood, coal, and refined oil products (gasoline, oil, diesel fuel, heating oil, natural gas, propane…)
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent Different greenhouse gases (GHG) have different global warming potential values due to their specific characteristics and behaviour in the atmosphere. Using empirically derived and modelled simulations, these ratios are determined using carbon dioxide as having a value of 1 (one) by definition.
COP(nn)	Conference of the Parties Annual conference to discuss progress (more accurately, lack thereof) by signatories to the treaty (countries) and multi-national corporations seeking to impede progress (quite successful to date). The roughly annual conferences are usually referred to as COPnn, where nn marks the number of conferences since the UN Framework Convention on Climate Change came into force in 1994. Enormous amounts of jet fuel are burned to get delegates, press, lobbyists, and various hangers-on from around the world to and from the event
Dry biomass	Biomass which has been dried (heat, blown air, desiccation) to remove as much water as possible
Eutrophic	A lake or pond that is rich in mineral and organic nutrients, leading to excessive growth of algae and aquatic plants, which reduces the dissolved oxygen in the water.
GHG	Greenhouse gas A number of gases occur in the Earth’s atmosphere which have the ability to warm the planet. This is a good thing for humans in a stable, typical range. Prior to the Industrial Revolution, the global average temperature during the time humans have resided on the planet has been around 13 -14 degrees Celsius. This is the stable environment in which our species evolved and thrived. Outside a fairly narrow band of temperatures, say 12 -16 degrees Celsius average surface temperature, we likely won’t fare so well, as the climate will become less stable, creating less hospitable conditions for our survival, food crops or livestock.
Gigatonne (GT)	One billion (thousand million) tonnes
GWP	Global warming potential
GWP_{XX}	Global warming potential for timeframe (years) According to the IPCC, the 100-year global warming potential (GWP_{100}) value for methane is 28, while the 10-year figure (GWP_{10}) is 104, compared with a GWP value of 1 for carbon dioxide (CO_2) for the same time spans. In other words, if one considers the GWP value for methane for its typical

	actual life in the atmosphere (a decade), it's 4 times higher than the number for a century, which industry and governments typically use to downplay the issue. Spoiler alert: we don't have a century left to fix this.
Hypereutrophic	A lake characterized by high algal productivity, intense algal blooms, fish kills due to oxygen depletion in the bottom waters, impairment due to frequent recreational use
IPCC	United Nations Intergovernmental Panel on Climate Change[79]
Kilotonne (KT)	One thousand tonnes
Megatonne (MT)	One million tonnes
Methane	A compound of carbon and hydrogen, gaseous at STP
Natural gas	The gas extracted from wells and shale-fracturing operations which is primarily methane, but typically includes small amounts of other gases such as hydrogen sulphide, ethane, propane, butane, pentane, nitrogen and carbon dioxide
Nitrogen oxide, nitrous oxides	Generic name given to many compounds composed solely of nitrogen and oxygen, many of which are products of combustion (nitrogen and oxygen are the two most common elements in the atmosphere)
NO_X	aka NOX (pronounced 'knocks' (see nitrous oxides)
N_2O	Dinitrogen oxide, aka nitrogen oxide or laughing gas (– see nitrous oxides)
OC	Organic carbon
SO_2	Sulphur dioxide (associated with acid rain)
STP	Standard temperature and pressure, essentially the environmental conditions found at sea level on a warm day. (As defined by the U.S. National Institute of Standards and Technology (NIST): 1 atmosphere pressure, 20 degrees Celsius (68 degrees Fahrenheit)
Tonne (T)	One thousand kilograms
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
Wet biomass	For this paper, comprises microalgae, macroalgae and other aquatic plant mass which has been removed from the water, drained but not dried, as would be appropriate for use in a biodigester or composting

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