Carbon and permafrost: the devastating positive feedback loop

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1 Introduction and Impact

The Canadian Arctic coastline is not a hospitable place to live. The few who do brave the bitterly cold winters and months-long polar nights live a subsistence lifestyle off of the land, hunting for Caribou and fishing in the frigid waters of the Arctic Ocean [1]. Some may be tempted to think that the warmer temperatures associated with climate change would be welcomed in such an environment, but this couldn't be further from the truth.

The community of Tuktoyaktuk, Northwest Territories, is located at a natural harbour on the Arctic coast. The area has been inhabited by the Inuvialuit since ancient times, and a permanent settlement was established in the early 1900s [2]. But now, many of the houses built on the coastline are under threat of being eroded into the sea, swallowed up by the advancing Arctic Ocean [3]. But what is the culprit behind the sudden advance in erosion? The answer is melting permafrost.

This far north, the yearly average temperature is far below freezing point. As a result, the ground, whose yearly temperature variation is much lower due to thermal lag [4], is frozen year round below the very top layer. This perpetually frozen ground is called permafrost, and it gives the ground a few important properties. Among these are the storage of frozen water and carbon, and the ground's relative hardness. The hardness of the ground presents a huge infrastructural challenge, as it acts as a bedrock that comes within feet of the ground's surface. Pipelines lay on top of the ground instead of being buried, and houses have to be built on stilts driven deep into the permafrost to avoid destabilising every summer when the top layer of soil temporarily thaws [5]. Building like this creates stable surfaces on which to build on, provided the permafrost stays frozen. This, however, is no longer the case.

As global temperatures rise, the Arctic warms even faster [6]. As a result, the top layer of permafrost is slowly beginning to thaw. Not only does this melt the ice that makes the ground that the infrastructure is fastened to stable (to disastrous consequences [7]), it also makes the carbon in the permafrost available for decomposition into carbon dioxide and methane [8]. These greenhouse gases, once released from the ground, begin a positive feedback cycle in which melting permafrost warms up the planet, thus melting more permafrost. Not only does this have huge local implications for those that live on the melting permafrost and the fragile environment they rely on, but also for the wider world, which will bear many of the effects of the melting permafrost feedback cycle.

This report will analyze a mathematical model from a permafrost implementation of the Hector carbon-climate model [8] that relates increasing average temperatures to a reduction of the proportion of the ground which is permafrost. It will then discuss the consequences of melting permafrost on human infrastructure and the wider climate, and the possible adaptation and mitigation strategies we could employ against these consequences, along with the ethical issues these present to people and the environment.

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2 Mathematical analysis and interpretation

1. The definition of ΔC_{perm} in section 2.1 of the Woodard paper [3] is

$$\Delta C_{perm} = (f_{frozen}(t) - f_{frozen}(t-1)) \cdot C_{perm}(t-1). \tag{1}$$

Since f_{frozen} is a decreasing function of t, ΔC_{perm} is negative. This has introduced a sign error into the definitions of C_{perm}, which is now increasing over time, and C_{thawed}, now decreasing with time. We correct the sign error by redefining f_{frozen} as $1 - f_{frozen}$. Equation (1) becomes

$$\Delta C_{perm} = ((1 - f_{frozen}(t)) - (1 - f_{frozen}(t-1))) \cdot C_{perm}(t-1),$$

which equals

$$(f_{frozen}(t-1) - f_{frozen}(t)) \cdot C_{perm}(t-1)$$

as desired.

2. Instead of using a unit time step model, we instead use Δt.
$(f_{frozen}(t-1) - f_{frozen}(t))$, the negative of the unit time step, becomes $-\Delta f_{frozen}(t)$, whilst $C_{perm}(t) - C_{perm}(t-1)$ becomes ΔC_{perm} and $C_{thawed}(t) - C_{thawed}(t-1)$ becomes ΔC_{thawed}.

The unit time step equations from the Hector model can be rearranged:

$$C_{perm}(t) = C_{perm}(t-1) - \Delta C$$

becomes

$$\Delta C_{perm}(t) = -\Delta C$$

and

$$C_{thawed}(t) = C_{thawed}(t-1) + \Delta C - F_{thawed-atm}$$

becomes

$$\Delta C_{thawed}(t) = \Delta C - F_{thawed-atm}.$$

As $\Delta t \to 0, \quad \Delta Var(t) \to \frac{dVar}{dt}$.
ΔC_{perm} becomes $-\frac{df_{frozen}}{dt} C_{perm}$ and our new equations for $\Delta C_{perm}(t)$ and $\Delta C_{thawed}(t)$ become

$$\frac{dC_{perm}}{dt} = \frac{df_{frozen}}{dt} C_{perm} \tag{2}$$

and

$$\frac{dC_{thawed}}{dt} = -\frac{df_{frozen}}{dt} C_{perm} - F_{thawed-atm}. \tag{3}$$

3. We are given $f_{frozen} = f$ with $f(0) = 1$ and $f(t) \to 0$ as $t \to \infty$.
A function that fits this perfectly is $f = e^{-t}$, which once subbed into (2) as $\frac{df}{dt} = -e^{-t}$ gives us

$$\frac{dC_{perm}}{dt} = -C_{perm} e^{-t}.$$

This solves to become

$$C_{perm} = c \cdot e^{e^{-t}},$$

where c is a constant to be found. Substituting the boundary condition $C_{perm}(0) = 1$ into our general solution, we get

$$C_{perm}(0) = c \cdot e^{e^0} = c \cdot e^1 = 1.$$

By rearranging to get $c = \frac{1}{e}$, we get $c = e^{-1}$. As $t \to \infty$, $e^{-t} \to 0$ and $C_{perm}(t) \to e^{-1}e^0 = e^{-1}$. This gives us

$$\lim_{t\to\infty} \frac{C_{perm}(t)}{C_{perm}(0)} = \frac{e^{-1}}{1} = e^{-1} \tag{4}$$

As desired. What this means in practice, is that this model would suggest the amount of Carbon stored in the permafrost would decrease to 37% of its current value.

4. Assume that $F_{thawed-atm} = \alpha C_{thawed}$, where $\alpha > 0$ is constant, and that

$$f_{frozen}(t) = \begin{cases} 1-\kappa t & if \quad 0 \leq t < \kappa^{-1} \\ 0 & if \quad t \geq \kappa^{-1} \end{cases}, \tag{5}$$

where κ is constant. For $0 \leq t < \kappa^{-1}$, equation (2) becomes

$$\frac{dC_{perm}}{dt} = -\kappa C_{perm},$$

which solves to

$$C_{perm} = c_1 e^{-\kappa t} \tag{6}$$

for $0 \leq t < \kappa^{-1}$. With the initial condition $C_{perm}(0) = M < 0$, we get $C_{perm}(0) = c_1 = M$, giving us

$$C_{perm} = Me^{-\kappa t}. \tag{7}$$

Equation (3) becomes

$$\frac{dC_{thawed}}{dt} = -M\kappa e^{-\kappa t} - \alpha C_{thawed},$$

which solves to

$$C_{thawed} = \frac{-M\kappa}{(\alpha - \kappa)} e^{-\kappa t} + c_2 e^{-\alpha t}., \tag{8}$$

again for $0 \leq t < \kappa^{-1}$. With the initial condition $C_{thawed}(0) = 0$, we get $C_{thawed}(0) = 0 = c_2 - \frac{M\kappa}{(\alpha-\kappa)}$, giving us

$$C_{thawed} = \frac{M\kappa}{(\alpha - \kappa)}(e^{-\kappa t} - e^{-\alpha t}). \tag{9}$$

For $t \geq \kappa^{-1}$, equation (2) becomes

$$\frac{dC_{perm}}{dt} = 0,$$

which solves to

$$C_{perm} = c.$$

The boundary Condition here is the assumption of continuity for C_{perm}, which gives us

$$c = C_{perm}(\kappa^{-1}) = Me^{-1},$$

which gives us

$$C_{perm} = Me^{-1} \tag{10}$$

for $t \geq \kappa^{-1}$. Equation (3) becomes

$$\frac{dC_{thawed}}{dt} = -\alpha C_{thawed},$$

which solves to

$$C_{thawed} = ce^{-\alpha t}.$$

As with earlier, the boundary Condition here is the assumption of continuity for C_{thawed}, which gives us

$$c = \frac{C_{thawed}(\kappa^{-1})}{e^{\frac{-\alpha}{\kappa}}} = \frac{M\kappa}{(\alpha - \kappa)}(e^{-1} - e^{-\frac{\alpha}{\kappa}})(e^{\frac{\alpha}{\kappa}}),$$

which gives us

$$C_{thawed} = \frac{M\kappa}{(\alpha - \kappa)}(e^{\frac{\alpha-\kappa}{\kappa}} - 1)e^{-\alpha t} \tag{11}$$

for $t \geq \kappa^{-1}$.

5. We are told temperature function $T_{air}(t)$ is linear. This means we know that $\frac{dT_{air}}{dt} = \beta$. By integration, we get $T_{air}(t) = \beta t + T(0)$, where the integration constant $T(0)$ is the initial average air temperature. Given the negative linear relationship between average air temperature and the fraction of permafrost remaining, then from the constants given to us in equation (5) we can determine that $\beta = \kappa \cdot \gamma$, where γ is a constant of proportionality, called Kessler's rate [8].

The main features of C_{thawed} are the initial speedy increase in C_{thawed}, followed by slowed increase, a peak, and a gradual decline. At $t = \kappa^{-1}$, C_{perm} flattens and C_{thawed} exponentially declines as $\rightarrow \infty$ (see Fig. 1).

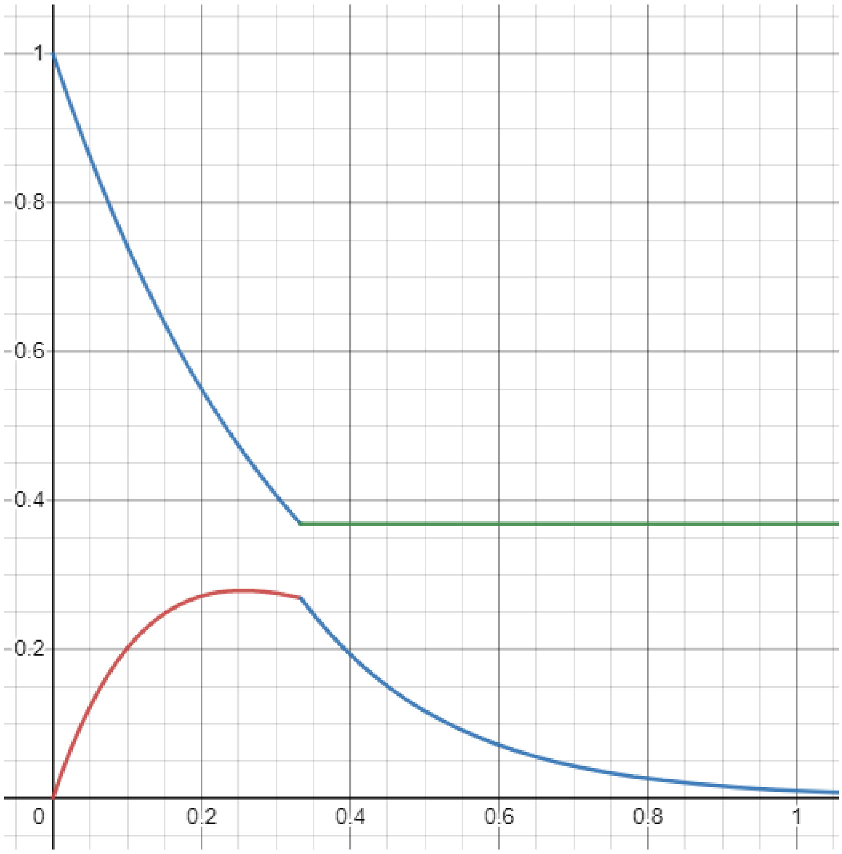

Figure 1: A graph of C_{perm} (blue - green) and C_{thawed} (red - blue) over time, for $M = 1, \kappa = 3$ and $\alpha = 5$.

The initial rapid growth of C_{thawed} is fuelled by the $-\frac{df_{thawed}}{dt}.C_{perm}$ part of (3), as the quickly melting permafrost directly adds to the amount of thawed carbon in the ground. Then, as the melting of the permafrost slows (as there's less left to melt), and $F_{thawed-atm}$ grows due to its proportional tie to the size of C_{thawed}, the proportional flux of carbon from the thawed ground to the atmosphere begins to outgrow the incoming thawing carbon, and C_{thawed} flattens, and begins to decline. Then, at $t = \kappa^{-1}$, f_{frozen} hits 0 and C_{perm} flattens. No more permafrost is melting, so with nothing feeding it anymore, C_{thawed} goes into exponential decline, and approaches 0 as time tends to infinity. As $F_{thawed-atm}$ is directly proportional to C_{thawed}, the expected pattern of carbon release over time would grow, peak and shrink with C_{thawed}.

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3 Policy and ethics

The implications of this model are damning. It confirms that in areas with rising average temperatures, we can expect a melting of the area's permafrost, followed by the emission of carbon dioxide and methane from the melted permafrost into the atmosphere. In a positive feedback loop, the greenhouse gas emissions will directly warm the planet, causing more permafrost to melt. This has repercussions on a local and international scale.

The communities built on top of permafrost rely on the permafrost staying frozen. Structures, including homes, roads and oil pipelines, are typically built on a foundation of stilts driven into the permafrost. If the permafrost around these supports melts, then the infrastructure that rests on it can become unstable. Furthermore, weakened ground by the sea is subject to higher rates of erosion, which is compounded by lower levels of sea ice removing a natural erosion barrier. Homes can destabilise and asphalt roads can crack and become impassable. This can make people homeless and can cut off communities from road networks [9]. Also, oil pipelines and containers spilling wreaks havoc on the local ecosystem, and is difficult to clean up in isolated areas. Adaptation strategies include using heat pipes to transfer heat away from the supports [10], but are often expensive. One method of mitigation is to build on thaw-stable permafrost [11], which is comprised of hard material like gravel or bedrock. However, this may not be possible. In such a desolate area, few locations are habitable and topsoil composition is comparatively less vital than other factors, like access to the sea. Another method of mitigation is relocation to permafrost-free areas, but the ethical issues lie thick here. Most communities built on permafrost are indigenous to the area, and relocation can alienate communities from their way of life [12].

One other direct consequence of melting permafrost lies in what lies frozen within the ground. In Longyearbyen, on the island of Spitsbergen, 7 people who died of influenza are buried in the permafrost, where they are perfectly preserved in the freezing temperatures, along with the virus that killed over 40 million people in 1918 [13]. If the permafrost melts, there is a danger of diseases that were otherwise extinct being revived. The mitigation strategy here is unique: terminally ill people are flown south to Norway and are buried there instead. However, in poorer communities, charter flights can prove too expensive, making this impossible.

The other effect of permafrost is that, once it has melted, microbes can convert the carbon within into greenhouse gases, which then gets released into the atmosphere, contributing to climate change [8]. This has implications on a global scale, with anthropogenic climate change being the biggest current threat to human civilization. Climate change contributes to rising sea levels, displacing millions [14]. Land that once received reliable precipitation can become increasingly susceptible to drought, reducing crop yields [15]. The mitigation strategy here is to emit fewer greenhouse gases, preventing further permafrost melting and slowing the positive feedback loop. However, implementation of this raises its own ethical questions, since carbon emissions is positively correlated with human development. Countries forced to emit less carbon may be stunted in their development [16]. Adaptation strategies are wide-ranging, but one that merits discussion is developing on areas at higher latitudes. These areas, now warmer as a result of climate change, would be more suitable for habitation. Unfortunately, this is easier said than done. Many of these areas, such as the Canadian Shield, are unsuitable for habitation due to their poor soil as well as their climate [17]. Others, like Patagonia in Southern Argentina, may get warmer on average, but will still lack adequate precipitation, making agriculture impossible [18]. In the places which will be habitable, there are wide-ranging ethical implications. Human habitation would require destruction of habitat for animals that live in the area, and development would likely require deforestation, further contributing to climate change and the melting of permafrost [19]. Other mitigation strategies are possible, like genetically engineering crops to withstand harsher climate [20] or building sea defences to protect the 50% of the Earth's population that live by the coast [21], but can be very expensive, and see diminishing returns as climate change gets worse.

The melting of permafrost is already affecting many Arctic communities, and is already contributing to climate change. The settlement of Tuktoyaktuk may eventually have to relocate [22], and the Arctic has already switched from a carbon sink to a carbon source [23]. Nevertheless, the negative effects of melting permafrost lie on a sliding scale, and mitigation is significantly easier and more effective than adaptation. The best way to combat the melting of permafrost is to reduce the scale of the positive feedback cycle by emitting fewer greenhouse gases and making sure that all the carbon frozen in the Arctic stays frozen.

Word count: 802

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