1 Diagnosing the Problem

The capture and removal of CO2 has been established as an integral of the solution to the imminent climate crisis. Experts believe that 49Gt out of the 59Gt we emit can be eliminated through industry decarbonization projects, leaving 10Gt of unavoidable GHGs (i.e. long-distance aviation or cement production). Carbon removal seems to be the only solution to neutralizing these 10Gt. Furthermore, even if we do invest in neutralizing this 10Gt, we will still face the effects of all of the carbon released to date. Therefore, widespread adoption of carbon capture and storage (CCS) is a necessary part of the solution. Two main barriers exist to the widespread adoption of CCS technologies: first, the high cost of quality CCS; second, the lack of incentive structures to encourage adoption.

The first barrier is that many CCS technologies are expensive, both in price and in opportunity cost. Even the cheaper technologies are around $200 per ton of carbon removed, and many of these technologies don't sequester the carbon long-term. Direct Air Capture (DAC) is around $600 per ton, costing $6T per year to remove all the unavoidable carbon. Other CCS initiatives are cheaper but have global capacity problems, are in the early stages of technological development, or the opportunity cost is too high. For example, we cannot cover the entire country of Brazil with trees in order to meet our capture targets. Why? Because the opportunity cost to the global economy, let alone to the Brazilians, would be very large.

The second barrier is that there is no existing widespread solution that incentivizes the adoption of CCS projects or technologies. Even if we reduced the cost of CCS technologies, there would still be little incentive for institutions to capture carbon. Possible incentive structures could be devised with government regulation. For example, a common proposal includes a scheme where the government sets a price for carbon (i.e. a carbon tax), so companies are incentivized to buy carbon offsets. However, the prices are not set by a self-regulating market. Experts agree that some form of government regulation is required in order to support the adoption of CCS technologies, either to create a self-regulated market (i.e. cap and trade program) or to simply set a price on carbon (i.e. carbon tax). Incentive structures for carbon capture can come from four places:

1. (Government) A top-down regulation mechanism that sets a price on carbon. This would immediately incentive both decarbonization and carbon capture technologies.

2. (Government) A regulation mechanism for a carbon credit market (i.e. cap and trade program).

3. (Market) The informal carbon market is when private companies elect to purchase carbon offsets to improve their public image or get to net zero.

4. (Market) Carbon treated as a resource that produces a product with an existing market.

Finally, building **trust** in carbon capture technologies is very important for any *government* solution (the first two listed above) or for an *informal carbon economy* (the third). One of the insidious factors that incentivizes low quality carbon offsets is greenwashing. Companies still get the profit benefits from claiming to use carbon offsets, when there is no validation system to verify that these offsets are actually reducing as much carbon as claimed. Further, any amount of carbon claimed to offset is sufficient for receiving the profit benefits. Companies are generally not willing to invest in proper carbon offsetting technologies because the cost outweighs the profit they would receive by seeming "greener". The second market solution listed above does not require a trusted validation mechanism because the more carbon that is removed, the more product there is to sell.

2 Potential Solutions

We want to maximize the amount of carbon removed from in the atmosphere, ideally removing at least 10Gt. We can treat this as a linear programming problem, where the decision variables are how many tons are removed from the atmosphere by each CCS initiative. In this model, the price per ton refers to the price of long-term sequestration (geological time scale) per metric ton of carbon. Informed policy is extremely important to effectively allocate our limited number of resources. By using the model I have designed below, we can effectively inform grant providers, private companies, policy makers, (or even) an RISC researcher (!!) on how to effectively allocate resources for CCS initiatives.

Constraints and Parameters: The problem is constrained by the budget and the total global capacity. I estimate the total amount of money that can be dedicated towards CCS is $75B per year. This is exactly 10 times the current global capacity of CCS investment. Although this is a relatively optimistic number, the current trajectory of CCS investment is positive.

CCS Initiative	Price (per ton)	Capacity	Sequestration Efficiency
DAC	$600	none	
Direct Ocean Capture (DOC)	$100	100,000 tons per year	
Temperate Rainforest Restoration	$281	150M hectares	2.7T per hectare
Tropical Rainforest Restoration	$25.9	287M hectares	4.4T per hectare
Biochar	$194	15M tons of biomass	0.95Ts / Feedstock ton
Coastal Wetland Preservation	$4	44.5M hectares	1.8T per hectare
Seaweed Farming	$3600	240M hectares	3.2T per hectare

Table 1: Price and Capacity of CCS Technologies

Table 1 shows how some carbon capture solutions have high cost, but have higher capacity.

Solution: The code for this model is in the appendix. I was able to optimize the total carbon sequestration by CCS technology as shown in Table 2. This solution is a greedy algorithm, prioritizing the highest carbon-to-dollar technologies.

CCS Initiative	Tons Removed
DAC	0
DOC	.0001Gt
Temperate	0
Tropical	1.2Gt
Biochar	.2Gt
Wetland	.08Gt
Seaweed	0
Total	1.56Gt

This suggests that with $75B globally per year, we can remove 1.56Gt out of the atmosphere per year, pushing our tropical reforestation, biochar creation, and wetland redevelopment to the maximum, and pushing our Direct Ocean Capture capacity to .0001Gt.

3 RISC Research Solution

In the solution above, we do not invest in Seaweed Farming because the price per carbon ton is very large. However, the exciting property of Seaweed Farming is that there is room for $12k in profit margin per hectare. If as a society, we invest $75B in CCS, coming from both government and private markets, the optimal solution is the following:

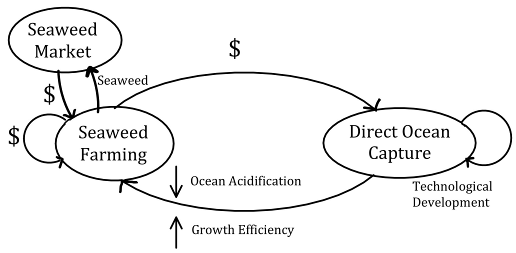
CCS Initiative	Tons Removed
DAC	15Gt
DOC	.0001Gt
Temperate	.4Gt
Tropical	1.2Gt
Biochar	1.3Gt
Wetland	.08Gt
Seaweed	.77Gt
Total	19Gt

By reallocating the resources gained from seaweed into Direct Carbon Capture (DCC) technologies (mostly to Direct Air Capture), we can remove ∼5x as many gigatons of carbon from the atmosphere.

This solution is practically difficult because the resources received from Seaweed Farming would not necessarily be entirely allocated to DAC and DOC without an institution. However, this exercise demonstrates that the global CCS resources can be allocated more effectively. Further, this scheme would provide more necessary initial funding for the development of DAC and DOC, ideally reducing the price per ton of carbon in the future.

From this model, my proposal as an RISC researcher would be to develop a self-regulating scheme, where Seaweed Farming and DCC technologies work in conjunction. RISC could serve as the intermediary between Seaweed Farming and DCC, by reallocating profits from Seaweed Farming to DAC and DOC. I will demonstrate how a symbiosis between Seaweed and DCC can exist, to generate an economically autonomous cycle. Specifically, I would develop a two part scheme (a larger diagram is in the Appendix):

- The profits from Seaweed Farming will be reallocated to DOC & DAC. Such funds would cover operating costs. Operating DCC technologies will result in technological development and scaling of these technologies.
- The DOC & DAC reduce the ocean acidification and improve the efficiency of Seaweed growth. Direct Ocean Capture is significantly more effective at carbon removal, and thus would have a higher impact on improving seaweed production.



I will now lay out a more specific set of steps as a RISC researcher. First, identify high potential seaweed farming locations and Direct Ocean Capture locations globally. Identify the intersection between these locations. Connect local farmers to assessment toolkits and work with Direct Ocean Capture developers. Initial funding could be from ARPA-E or other government/research sources. Then, allocate a portion of the profit margin to the local farmers to incentivize continuation of collaboration. The rest of the profit margin can be allocated to the operating costs of DOC and DAC. Upfront costs could be covered by government agencies funding.

According to Drawdown, the total addressable market of Seaweed Farming is around 240 million hectares farmed every year. The commercial seaweed market is currently at $17B. This market is expected to approximately double by 2030. Since the market is growing, there is room for seaweed to generate sizable profit. Additional seaweed-based products are entering the market as well (i.e. cattle feed or cosmetics).

This solution theorizes how a symbiosis can be created between two carbon capture solutions, accelerating the development of both. As more seaweed farms fund DCC technologies, DCC will continue to technologically develop, ideally becoming cheaper. Further, by incentivizing the establishment of such facilities, less activation capital is required. Governments or private company grants can be directed towards increasing the capacity of existing facilities.

4 Limitations & Extensions

I will now describe three limitations to the scheme above.

First, seaweed farms have a low capacity globally, at around 240M hectares, or equivalent to .77Gt of carbon sequestered. It is very unlikely that seaweed will be the sole - or even main - carbon sequestration technology to meet our targets. This scheme demonstrates how we can quintuple the carbon removed from the atmosphere by reallocating resources from the absolute maximum capacity of seaweed farms. However, it is likely we will need a variety of carbon removal technologies to meet our goals.

Second, there may be no incentive for Seaweed Farmers to work with this scheme. I did not calculate the revenue gained by reducing the local ocean acidification. It is possible that the financial benefits of DCC technologies to improve the efficiency of seaweed growth *does not* outweigh the cost of funding DCC. Seaweed farmers may be better off not working with RISC at all and pocketing the profits.

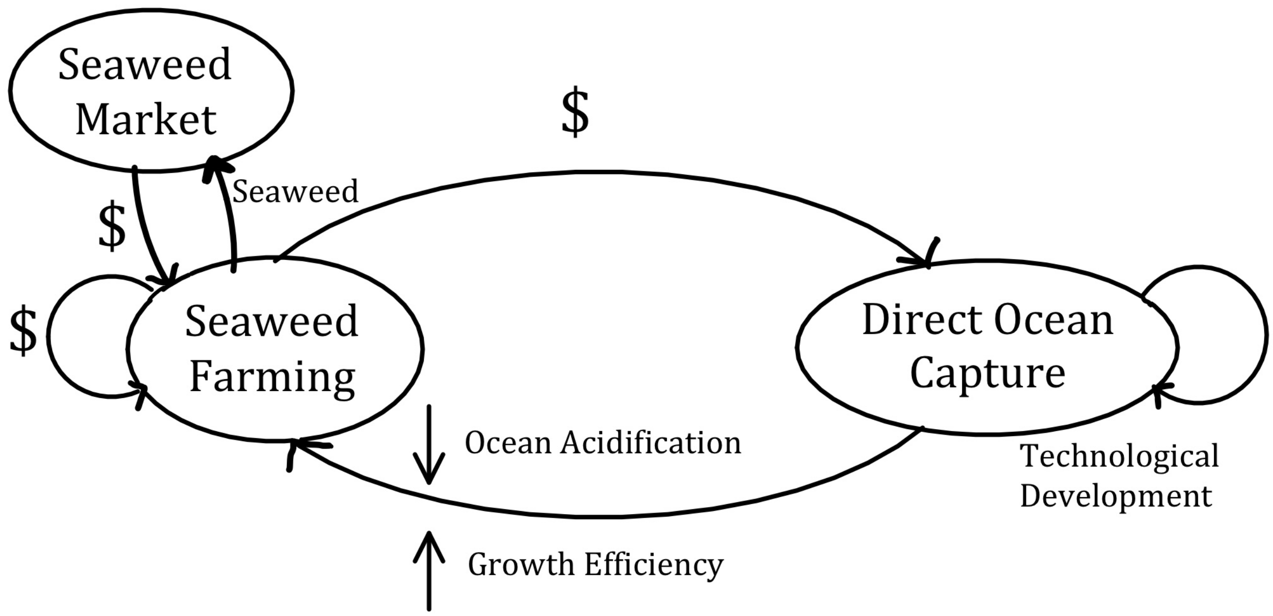
Third, Direct Ocean Capture is in a relatively early technological development. Thus, the technology requires a high upfront cost. Upfront costs were not included in the model, which could be a large hindrance on the tractability of DOC.

There are several extensions to the above proposal. Other technologies exist that use carbon capture to produce a product with an existing market (i.e. bricks or tires). I'm choosing seaweed farming because of the existence of research and data. As an extension of this, a RISC researcher could act as an intermediary and identify carbon capture technologies that produce for an existing market efficiently.

This model does not take into account the time capacity and sequestration capacity of each CCS technology. Each natural sequestration mechanism has some amount of carbon that is sequestered on the geological time scale per year. Although the sequestration capacity above only refers to the geological time scale sequestration, there is shorter-term sequestration that varies per solution. This suggests that the amount of carbon sequestered needs a time dimension in the model above.

5 Appendix - No need to read

5.1 Diagram



5.2 Reflections

I very much enjoyed this exercise! Thinking about such problems from a strategic perspective was exciting. I'm a little embarrassed about the simplicity of the solution after all that work, but sometimes - maybe even often - the simplest solutions are the best. A lot of details need to be ironed out. Implementing this project would require a lot more research, including interviews with farmers to determine if such a scheme is desirable. Further, many of these numbers need to be validated.

5.3 Demonstrating Importance of Variety

CCS Initiative	Tons Removed
DAC	.568Gt
Temperate	.4Gt
Tropical	1.2Gt
Biochar	1.3Gt
Total	3.59Gt

This suggests that with $75B globally per year, we can remove 3.5Gt out of the atmosphere per year, pushing our temperate, biochar, and tropical technologies to the maximum, and pushing our DAC capacity to .56Gt, or investing around $60B in DAC technology. DAC is, however, not cost efficient. More newly popularized solutions such as Seaweed farming and Mangrove tree restoration (Wetland restoration) can reduce the investment in DAC and increase the total number of tons reduced because of the higher cost efficiency.

5.4 Code

Code for the above Linear Programming. Small changes to the data were made for the various scenarios presented.

```
set Technologies;

param price {Technologies};
param capacity {Technologies} >= 0;
```

```
var tons {Technologies} >= 0;

maximize TonsRemoved: sum {t in Technologies} tons[t];

subject to Cost:
   sum {t in Technologies} price[t]*tons[t] <= 75000000000;
subject to Capacity {t in Technologies}:
   tons[t] <= capacity[t];
```

The data file was structured as follows:

```
set Technologies := Temperate Tropical Biochar DAC DOC Wetland Seaweed;

param: price :=
  Temperate 281
  Tropical 25.9
  Biochar 194
  DAC 600
  DOC 100
  Wetland 4
  Seaweed -12892;


param: capacity :=
  Temperate 400000000
  Tropical 1262800000
  Biochar 1360000000
  DAC 1000000000000000000
  DOC 100000
  Wetland 80100000
  Seaweed 770000000;
```