Seaweed in the earth system

This written version of the talk I gave at the seaweed festival has to be short so much of the thinking that went into it is hidden. I have therefore included a list of references and notes along with answers to some of the questions I was asked.

Preamble: A finite world

The things that I am talking about are a patchwork of fragments that are part of a larger understanding of the earth system and because of this, I feel I must frame what I am saying with a warning about the future.

Fifty years ago the Apollo missions had reached the moon and shown us the earth as a blue cloud bound ball of sunlit half-darkness hung in an infinite void and an engineer, economist, mathematician wrote a computer program to model all the possible futures of a technological civilisation in a finite world. His students published the results as *The Limits to Growth*. (The back story of those people is not widely known, it should be!)

In 1973 when *The Limits to Growth* was published the authors found that it was possible for our civilisation to choose to follow a path that led to stability. Ten years later when they published their first ten yearly update to *The Limits to Growth* they found that the collapse of our civilisation is unavoidable so that now the only question left to answer is something like, *How should we live with grace in a dying world?* (I did not have an answer then and do not have one now but I think that asking that question creates a space for constructive thinking.)

I still hope that if we are lucky and if we can work together, as we have never worked together before, we can prevent the collapse of our civilisation and with it the great loss of life that will follow, or at worst leave some of the staggering richness of the earth intact in the ruin we leave and that some people will live to tell stories, to dance, and to watch their children become adults with delight.

A finite world

Earth rise, photographed from Apollo 10's Lunar Module in orbit round the moon.

Edgar Mitchell, Lunar Module Pilot of Apollo 14, said, *"You develop an instant global consciousness, a people orientation, an intense dissatisfaction with the state of the world, and a compulsion to do something about it. From out there on the moon, international politics look so petty. You want to grab a politician by the scruff of the neck and drag him a quarter of a million miles out to the moon and say, "Look at that, you son of a bitch."*

Without the moon no tides and no salt marshes.

Photograph: NASA

Since this is a talk about the earth system it is necessary to include some outline information about the carbon cycles and stores that humans have been altering. The size of some of these pools and fluxes are known with reasonable accuracy, others are estimates, though estimates made on the basis of careful thought and a centuries work by climatologists, geologists, oceanographers, and biologists. In order not to interrupt a talk that is essentially about seaweed I have put these figures in an appendix.

Now I will talk about seaweed

Seaweed, (macroalgae), are thousands of species of marine algae and it was not until the mid-twentieth century [10 for example] that the distribution and abundance of seaweeds began to be mapped in detail.

I will ignore this definition occasionally and include other marine algae in this talk because of the large part they play in the earth system.

It makes very little sense to think about any plant or animal in isolation, all of them are tangled in relationships that seem strange beyond strange. John Muir wrote. *"When we try to pick out anything by itself we find that it is bound fast by a thousand invisible cords that cannot be broken, to everything in the universe."* But it seems to me that even this does not begin to capture the strangeness of the relationships that tangle and bind ecosystems in balance. In the Blind Watchmaker, Richard Dawkins wrote about how living things are created without conscious design. (He was inverting an argument made by William Paley in 1802 for the existence of a creating deity.) While that analogy is useful for thinking about individuals the relationships between species in ecosystems are frequently so unexpected that I think it more useful to imagine them being assembled by a dreaming blind watchmaker.

The ecosystem the first people of the coast from Baja California to Alaska knew contained kelp forests, sea otters, orcas, grey whales, salmon, sea urchins, and Steller's sea cows. Then Russians came and with the help of the Aleut hunted the sea otter almost to extinction for their pelts. Sea otters eat sea urchins which eat kelp so with nearly all of the sea otters gone the sea urchins proliferated and ate the kelp. And that loss of kelp is thought to be the primary cause of the extinction of Steller's sea cow which lived in the sea around the Kmandorski islands. (Bering island, Medny island, and fifteen smaller islets and rocks). When sea otters were finally protected in 1911 and began to control the numbers of sea urchins again the kelp forests slowly regrew. It is as if we have been removing cogs at random from the blind watchmakers watch for centuries without understanding how the watch works and were then puzzled when the watch stopped. But we also hunted the grey whales which migrate between Baja California and Alaska, as their numbers were reduced the number of sea otters also fell. It took a while for ecologists to find out how the kelp forest, grey whales, and sea otters were connected. In an undisturbed food web, in a watch with all its cogs, orca hunt grey whales but as the number of whales fell, the orca were forced to find another food source and started hunting sea otters. So in a repeat of the first catastrophe with fewer sea otters to control their numbers, the sea urchins proliferated again and ate the kelp faster than it could regrow and the kelp forests began to thin. See [11] and [12] for the whole story. These recent examples of the unintended effects of exploiting an ecosystem without understanding it and the resulting extinction of Steller's sea cow show how deliberate and accidental modification of habitat can lead to extinction. It seems likely that similar processes were factors in the extinction of the megafauna that occurred as humans migrated out of Africa and spread throughout the world.

For the last few million years, the earth has been cold with only short warmer interglacials and life has adapted to the cold so that the sudden warming caused by humans burning fossil fuels is now stressing ecosystems. A heatwave along the coast of California in 2013 almost wiped out the sunflower sea star, the main predator of sea urchins, resulting, just as the hunting of sea otters did, in a 95% reduction in the area of kelp forests. This matters because kelp forests, like terrestrial forests, capture carbon dioxide slowing down the rate of global heating. And they, like terrestrial forests, provide habitat for marine life so that without them the fisheries we depend upon for food and work crumble. [13, 14]

I suspect that events like the ones that occurred along the Pacific coast of the Americas must have taken place along the Atlantic coasts of Europe during the years before records were kept and ecological understanding existed so that now we live in an altered environment with no memory of its former richness.

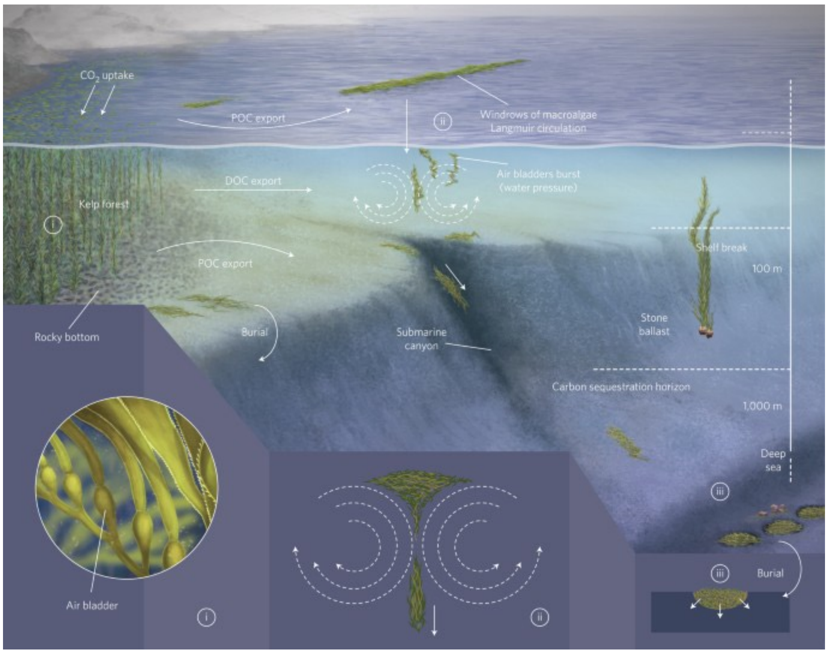
An ecosystem woven together by kelp

A raft of sea otters (*Enhydra lutris*) resting in a group
Photo by U.S. Fish and Wildlife Service

An adult grey whale (*Eschrichtius robustus*) and its calf.
Picture: José Eugenio Gómez Rodríguez

Transient orca (*Orcinus orca*)
Photo: Rennett Stowe

Giant kelp (*Macrocystis pyrifera*). California, Channel islands
Photo: Claire Fackler, CINMS, NOAA.



Pathways for sequestration of macroalgae carbon into the deep sea. As macroalgae grow, they removes carbon dioxide from the atmosphere. Most of the carbon sequestered by macroalgae is sent to the deep sea either in the form of dissolved carbon or in the form of plant detritus which easily floats out to sea thanks to gas-filled bladders.

Macroalgae sequester about 0.173 gigatonnes of carbon per year.

From Krause-Jensen and Duarte, 2016.

Seaweed and sediments are a carbon store and sink

It is only during the last few decades that we have begun to accurately measure the global fluxes and stores of carbon! [15] The size of global carbon pools are approximately:

38,200	Gt of carbon is stored in the oceans (in the form of bicarbonate and carbonate ions)
2,700	Gt of carbon is stored in soils
875	Gt of carbon is stored in the atmosphere (2014)
580	Gt of carbon is stored in all living organisms

10,000 years of agriculture has reduced the global store of soil carbon by 116 Gt

Annual carbon emissions from fossil fuel burning are roughly 9.88 Gt C (36.2 Gt CO_2)
Annual carbon emissions from land use change are roughly 1.51 Gt C (5.5 Gt CO_2)

Some of this CO_2 is absorbed by the ocean and by plants slowing down (slightly) the rate at which the concentration of CO_2 in the atmosphere is increasing.

Krause-Jensen [16] estimates that macroalgae sequester about 0.173 gigatonnes of carbon per year. About 90% of this sequestration occurs through export to the deep sea, and the rest through burial in coastal sediments. This estimate exceeds that for carbon sequestered in angiosperm-based coastal habitats. [See also 18] This is small compared to anthropogenic carbon emissions but it goes on year after year, millennia after millennia so that after a thousand years macroalgae will sequester 173 gigatonnes of carbon

Mearl - a coralline algae - is a carbon sink and store

Maerl is at least three species of slow growing coralline algae that grow loose in beds of fragmented nodules in the sub-littoral zone. Maerl contains 32.1% $CaCO_3$ (calcium carbonate) and 3.1% $MgCO_3$ (magnesium carbonate) by dry weight. It accumulates in deep beds over millennia and hence results in the sequestration of carbon on a geological timescale.

A queen scallop on maerl
Picture NatureScot

A painted goby on the North Strome maerl bed, Loch Carron
Picture NatureScot

Maerl is also, like kelp, a habitat - think of forests - if thew trees are felled then all of the life that belongs with them is extinguished.

In Europe, it is dredged from the sea floor and used as a soil conditioner. This destroys a vital habitat and a carbon store. The slow growth of maerl means that there is no possibility of its growth keeping up with the losses due to dredging. The ancient practice of extracting maerl from beaches and later by dredging, centuries before it was known that it forms a habitat for other marine life, is an example of a traditional practice, that because it is traditional, is thought of as honourable so that it is difficult to stop it for the common good.

Grall and Hall-Spencer [17] write, *"Today, Breton maerl is extracted at ca 500,000 tonnes per year and used in a variety of industrial processes including agriculture, water purification, mineralization and the manufacture of cosmetics..."*

...and *"Maerl extraction in Brittany is now under the control of the French mining management scheme, with quota schemes (80 000 metric tons in 2001 on the Glenan bank) and regular environmental surveys. However, such quotas are not compatible with regeneration of the resource the situation is akin to harvesting peat on land where removal far outstrips production."*

I think stronger words are needed so, dredging seems closer to driving a bulldozer through a cathedral to collect the splintered wood of the pews for fire wood.

Sail and muscle powered and industrial maerl dredging in Brittany

Do not underestimate the power of tradition to literally terraform the planet!

See, for example, the discussion of a choice of a marker for the start of the anthropocene. One suggestion is that we use the rise in CH_4 caused by rice farming which began 5,020 years before the present. It is thought that this may have prevented the reglaciation of the Earth.

Simon L. Lewis & Mark A. Maslin. (2015) Defining the Anthropocene, Nature, March 2015.

Ruddiman, W. F, et al. (2016) *Late Holocene climate: Natural or anthropogenic?* Reviews of Geophysics, vol. 54, Issue 1.

A digression to phytoplankton

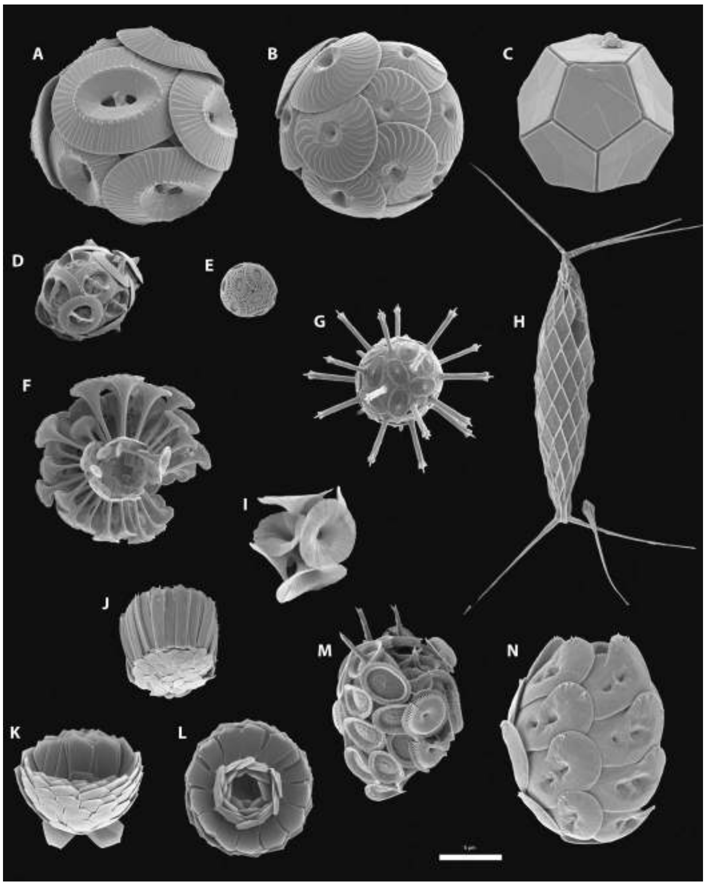
Marine phytoplankton perform half of the global photosynthetic CO_2 fixation (net global primary production of about 50 gigatonnes of Carbon per year) and half of all oxygen production despite amounting to only ~1% of global plant biomass. [19]

Coccolithophores a component of the phytoplankton (alga) and, Coccoliths, the shells of the Coccolithophores are the main component of Chalk

Chalk was formed in the Cretaceous, between 99 and 65 million years ago. It was deposited on extensive continental shelves at depths between 100 and 600 metres (330 and 1,970 ft), during a time of nonseasonal (likely arid) climate that reduced the amount of erosion from nearby exposed rock. The lack of nearby erosion explains the high purity of chalk. The coccolithophores, foraminifera, and other microscopic organisms from which the chalk came mostly form low-magnesium calcite skeletons, so the sediments were already in the form of highly stable low-magnesium calcite when deposited.

Coccolithophores are of concern to those studying climate change because as ocean acidity increases they may begin to have difficulty forming their shells in the more acid water so that the size of the carbon sink they create decreases.

(I made a very rough estimate of the total global mass of chalk and find that it is at least an order of magnitude more than the mass of the earth's atmosphere.)



Diversity of coccolithophores

Emiliania huxleyi, the reference species for coccolithophore studies, is contrasted with a range of other species spanning the biodiversity of modern coccolithophores. All images are scanning electron micrographs of cells collected by seawater filtration from the open ocean.

(A to N) Species illustrated:

(A) Coccolithus pelagicus
(B) Calcidiscus leptoporus
(C) Braarudosphaera bigelowii
(D) Gephyrocapsa oceanica
(E) E. huxleyi
(F) Discosphaera tubifera
(G) Rhabdosphaera clavigera
(H) Calciosolenia murrayi
(I) Umbellosphaera irregularis
(J) Gladiolithus flabellatus
(K and L) Florisphaera profunda
(M) Syracosphaera pulchra
(N) Helicosphaera carteri.

Scale bar, 5 µm.

From Wikipedia

Phytoplankton terraformed the Earth

The shells of the Coccolithophores formed chalk

Old Harry Rocks are three chalk formations, including a stack and a stump, located at Handfast Point, on the Isle of Purbeck in Dorset, southern England. They mark the most eastern point of the Jurassic Coast, a UNESCO World Heritage Site

Back to macroalgae and Seaweed farming

The total global production of seaweed was 28.5 million tonnes in 2014
5.7 million tonnes of this was harvested annually from natural beds [21]

In 2014, the total annual production of Asian-Pacific seaweed aquaculture beds surpassed 2.6 million tonnes (dry weight.) [21]

Farming nori in Ago Bay, Mie prefecture, Japan
(Getty Images)

Seaweed farming in Zanzibar
(IUCN)
Two species of (imported) red seaweeds are farmed, Eucheuma denticulatum (E. spinosum) and Kappaphycus alvarezii (E. cottonii)

Each year, on 14 April, Japanese seaweed farmers gather on a headland overlooking the Ariake Sea, a deep notch carved out of the southern island of Kyushu. Many of the farmers make their living in the waters below, others travel from coastal towns and villages elsewhere in Japan. They come to celebrate the life of a woman who lived and worked in Manchester, in the industrial north of England. Kathleen Drew had no connection with Japan, except for one thing an enthusiasm for seaweed, and in particular a silky, reddish weed called Porphyra...

...Drew never found out that her botanical detective work had saved Japan’s seaweed industry: she died in 1957 at the age of 56. But the nori growers knew how much they owed her. On 14 April 1963, they unveiled a polished granite memorial bearing the likeness of the woman they called the Mother of the Sea. And they have been back to pay their respects – and bring offerings of seaweed – every year since.

Stephanie Pain, *Riddle of the fronds*, New Scientist, 16 April 2004

Global seaweed harvest from wild beds (in metric tonnes) 1950–2014 (FAO, 2014) [Table 1. from 21]

Years	Europe	Asia	Africa	Americas	Oceania	Total
1950–1959	2,467,334	2,708,688	275,000	1,405,962	2,500	6,859,484
1960–1969	3,919,564	3,419,110	434,000	2,106,645	40,500	9,919,819
1970–1979	4,017,962	3,232,250	518,138	2,955,364	89,067	10,812,781
1980–1989	4,353,710	3,429,709	265,344	2,866,262	158,372	11,073,397
1990–1999	3,602,827	5,045,122	227,679	3,216,902	244,238	12,336,768
2000–2009	2,823,367	4,321,926	313,290	4,128,532	103,145	11,690,260
2009–2014*	1,286,809	1,928,988	101,158	2,384,646	14,525	5,716,126

All farming consumes energy and emits carbon dioxide as an almost inevitable result of constructing and operating the farm as does transporting the crop to market. This is because the boats, engines (even if they are electric), and tools that the farm uses are constructed from materials that took energy to mine, smelt, transport and manufacture. Their use then consumes further energy.

I grew up in a culture that attempts to solve its problems by constructing machines and while some of these machines have transformed our wellbeing, think about sewing machines, washing machines, and electricity, the thoughtless use of machinery and energy has allowed us to sleep walk into a trap. We must now start to find ways to do more with less and only what we must do, acting only when we must act. In doing this we must design sustainable agroecological systems.

Know that third world farmers, most of whom are women, feed a large proportion of humanity, and in doing so manage to harvest 100 times more edible food energy than they burn as calories in planting, growing, and harvesting. They are 5,000 times more efficient at feeding people than intensive agriculture is, and do so without using much/any fossil fuel.

Geoengineering

With that warning in mind N'Yeurt, et. al. [23] have calculated that ocean afforestation (farming kelp in 9% of the ocean) would produce 12 billion tons of bio-methane (as fuel) and that when this is burned 34 billion tons of CO_2 could be captured from the combustion exhaust and buried. The growing kelp would capture 53 billion tons of CO_2 per year from the atmosphere, quickly reducing atmospheric CO_2 concentration to a preindustrial level. They also state that such a large area of kelp forest, if it is possible at a feasible energy and resource cost, would result in an increase in fish stocks. To be fair to the authors, I think they are exploring the outline of an upper limit and are not advocating such a large scheme.

But the problem with this scheme, and many others like it, is that it takes no account of the energy and material costs needed to create and operate the scheme or of the unintended damage that would follow if such a scheme could be put into operation. The earth is not infinite and we do not have an infinite supply of energy. And while nine per cent sounds like a small number nine per cent of the area of the Earth's oceans is equal to eighty per cent of the area of the North Atlantic, three times the area of the USA, twice the area of Russia, and four times the area of Brazil so I am sure that it could not be constructed and maintained. Nor do we yet know if carbon capture on the scale envisioned by the authors is possible, or how efficient it will be, (they assume 100%), nor do we know its energy cost. And even if only a small percentage of this kelp was grown on ropes I am sure that entanglement would drive the great whales to extinction. The trouble is that these schemes are frequently picked up by the media who uncritically report that climate change has been solved. The result is that it is easier for business to continue as usual.

This doesn't mean that we shouldn't try to restore kelp forests and to increase their area as much as possible. Rather that I am sure that a single scheme alone will not work so that we will have to use a patchwork of smaller marine and terrestrial schemes.

Above all we must do no harm

If left undisturbed, organic carbon stored in marine sediments can remain there for millennia. But disturbance of these carbon stores releases some of the stored carbon, increasing ocean acidification, and reducing the ability of the ocean to reduce the rate of increase of the concentration of atmospheric CO_2. Thus, protecting the sea bed is vital. Enric Sala et. al. [24] estimate that bottom trawling releases 1.47 gigatonnes of CO_2 per year which is equal to about 15-20% of the CO_2 absorbed by the ocean annually and is comparable to the global annual carbon lost from terrestrial soils caused by farming.

What should we do?

Stop all dredging. And stop bottom trawling in many, though not, all areas. And carry out as much ocean afforestation as is practical, and become far better stewards of the land because the land and its ecosystems are part of and connected to marine ecosystems. [25, 26]

I know this will be difficult, but it will be easier than asking ourselves how to live with grace in a dying world...

The following notes and references give more coherent answers to the questions I tried to answer at the end of the talk.

The predictions of The Limits to Growth show that there is no option other than to reduce the population and its impact on the environment. (A larger population is possible if and only if its impact on the planets environment is minimised.)

Someone pointed out that people living in the developing countries do far less harm than those in developed countries.

This is true. The problems that we face can only be solved by everybody together. In other words we must reduce population everywhere (by planned voluntary birth control) and this is as important in rich countries as it is in poor ones.

In order to minimise our impact on the environment we must do less with less. That means radically reducing energy and resource use in developed countries while increasing it as little as possible in the poorest areas and countries. I believe we should provide medical care for all people everywhere and social security and shelter for all people everywhere.

I believe that this just might be technically possible. The problems that must be solved relate to persuading humanity to work together and to somehow finding a way to govern that does not result in war and waste and poverty being inflicted by governments on their own citizens.

I think that the social sciences provide our only hope.

Anthropological knowledge

Ruth Mace gives two concrete examples of the value of anthropological knowledge to policy making:

In a letter she wrote to the journal Nature in 1993 she says, "*...Rapid population growth is a problem, because it increases poverty and ill-health in societies where it occurs. We will have more success at slowing world population growth if we see it as problem of enabling women in poor countries to have control over their own reproduction, which some carefully targeted development aid could go a long way towards achieving.*"

In an interview with New Scientist 19th June 2019 she comments on the design of the British social security system saying, "*...If the politicians who dreamed up that scheme had come to my class on human behavioural ecology, they might have realised that making life less predictable was going to make people's decision-making more short-term, not longer-term.*"

On a more mundane level if you want to know what people are doing or how they are structuring their lives or are dividing labour then ask an anthropologist.

Ruth Mace. (1993) Population control. Nature, 362. pp. 782, 29 April 1993

Peaceful revolutions

Someone asked about the changes in governance that will be necessary to prevent collapse and I talked about the need to speak truth to power and for civil disobedience to force politicians to accept that great changes in the way we live are necessary. I would much prefer that this can be done through education and without a revolution. However I think its is useful for anyone planning a revolution to know that it is an historical fact that peaceful revolutions produce better outcomes than violent ones.

There is too much to remember and I wrongly credited Marilyn Strathern with working on peaceful revolutions. It was Erica Chenoweth.

As a student of political science, Erica Chenoweth was taught to assume violence was the most effective way to achieve revolution. And then she decided to check. She and her colleague Maria Stephan collected data on 323 of the violent and nonviolent political campaigns that have taken place since 1900. They chose to analyse only those campaigns that involved at least a thousand activists and which brought about regime change within one year of starting. What they found was that nonviolent campaigns succeeded 53% of the time, whereas violent campaigns only succeeded 23% of the time. They think the reason nonviolent revolutions succeed more often is that they attract more people and those people are a mixture of all ages. They suggest that participants are willing to pass on information and take part in cooperative action during non-violent campaigns than are willing to risk doing so during violent ones. They also think that soldiers and police are reluctant to attack or kill a crowd that may include their mothers, sisters, and friends. And they found that the new government, composed of people who worked nonviolently, were better at working peacefully after the revolution and hence more likely to hold onto power and cause lasting beneficial change. Take note revolutionaries, (and governments intent on playing the great game).

Chenoweth, E., & Stephan, M. J. (2011) Why civil resistance works: The strategic logic of nonviolent conflict. Columbia University Press.

But read Marilyn Strathern anyway.

Education as storytelling for earthly survival

Education is above all else about the stories we tell about the cosmos we inhabit and about the work we value and the stories we tell matter. The historian, biologist, and social scientist Donna Haraway talks of *"Story telling for earthly survival."* She sees the need to change our stories and with them how we hold the world in our minds. She quotes the social anthropologist Marilyn Strathern, *"It matters what ideas we use to think other ideas with."* And goes on to say; *"It matters what matters we use to think other matters with; it matters what stories we tell to tell other stories with; it matters what knots knot knots, what thoughts think thoughts, what descriptions describe descriptions, what ties tie ties. It matters what stories make worlds, what worlds make stories."*

Donna Haraway went on to say, *"Marilyn Strathern wrote about accepting the risk of relentless contingency; she thinks about anthropology as; the knowledge practice that studies relations with relations, that puts relations at risk with other relations, from unexpected other worlds."*

That seems to me to describe how all learning (and the creation of art and story) contains the risks that come with all new knowledge. That opening doors is a risk. What will you see? What will come out, or go in? What friends will you make?

Donna J. Haraway. (2016) Staying with the Trouble: Making Kin in the Chthulucene, Duke University Press.

See also: Donna J. Haraway, Living and dying together on this planet: https://www.youtube.com/watch?v=z-iEnSz-tKu8 (Start listening bit after 1:11:53)

Strathern, Marilyn. (1988) The Gender of the Gift. University of California Press.

Advising governments

Peter Wadhams, a researcher at the British Antarctic Survey reports in his book about climate changes effects in the Arctic, A Farewell to Ice, how Nigel Lawson invited an unqualified member of a climate change denial think tank to advise a select committee rather than inviting someone who had been to the Arctic and had some qualifications. This kind of failure has to stop.

The following quotes are from:

MacKay, David J. C. (2009) Sustainable Energy - Without the Hot Air. UIT Cambridge Ltd.

The absence of scientific understanding often leads to superficial decision-making. The 2003 energy white paper was a good example of that. I would not like publicly to call it amateurish but it did not tackle the problem in a realistic way.

Sir David King, former Chief Scientist

Serving on the government's Renewables Advisory Board . . . felt like watching several dozen episodes of Yes Minister in slow motion. I do not think this government has ever been serious about renewables.

Jeremy Leggett, founder of Solarcentury

And the following story was told to the author thirty-five years ago by one of the members of the US President's Science Advisory Committee. He said that the committee had advised against the USA (Boeing) building a fleet of supersonic airliners (Similar to Concord) and that President Nixon had responded by shutting down the committee. He went on to say that had known president Nixon would respond to his advice in this way he would not have given it because the damage caused by the effects of the president depriving himself of competent advice far exceeded the damage that would have been done if the aircraft had been built. (When writing this I worried that I had forgotten or misremembered what had been said so I have checked.) The following is from Wikipedia:

In 1973, shortly after winning re-election in a landslide, President Richard Nixon, eliminated the the President's Science Advisory committee. Nixon was frustrated with what he saw as a lack of support from the committee for his administration's agenda, including a member of the committee that spoke publicly against his administration's support for research into supersonic transport. The White House Office of Science and Technology and the United States Congress were made to rely on federal agencies for guidance in scientific policy. A similar entity, the United States President's Council of Advisors on Science and Technology (PCAST), was established in 1990 by President George H. W. Bush, and renewed by three subsequent presidents.

https://en.wikipedia.org/wiki/President's_Science_Advisory_Committee

I mentioned that small farmers feed the world. The following gives some background to this.

The UN environment programme, the international fund for agricultural development, the FAO, and the UN Special rapporteur on the right to food all estimate that small farmers produce up to 80% of the food in the non-industrialised countries. [1, 2]

The introduction to, Hungry for land, [3] states: *'It is commonly heard today that small farmers produce most of the world's food. But how many of us realise that they are doing this with less than a quarter of the world's farmland, and that even this meagre share is shrinking fast? If small farmers continue to lose the very basis of their existence, the world will lose its capacity to feed itself.'*

They draw the following conclusions.

- The vast majority of farms in the world today are small and getting smaller
- Small farms are currently squeezed onto less than a quarter of the world's farmland
- We're fast losing farms and farmers in many places, while big farms are getting bigger
- Small farms continue to be the major food producers in the world

- Small farms are overall more productive than big farms
- Most small farmers are women

The authors discuss the uncertainties in the data in the report but have high confidence in their conclusions.

Note also that in much of the world an undocumented subsistence harvest is taken. This is almost universal in poorer countries and common in richer countries too. For example most of the small farms I know grow or barter most of their food and many people have allotments or use their gardens to grow food. In the villages I grew up in everyone grew (and foraged) some of their food.

1. Piero Conforti, Mario Giampietro (1997) *Fossil energy use in agriculture: an international comparison*. Agriculture, Ecosystems and Environment 65, pp. 231-243

2. Kanayo F. Nwanze. *Small farmers can feed the world*; UNEP, Small farmers report; FAO, Women and rural employment fighting poverty by redefining gender roles, (Policy Brief 5), IFAD.

3. GRAIN Report May 2014. Hungry for land, Small farmers feed the world with less than a quarter of all farmland.

4. Pimentel D. & Pimentel M. (2003) *Sustainability of meat-based and plant-based diets and the environment*. American Journal of Clinical Nutrition, 78 (suppl) 660S-3S.

5. For data on the energy cost of some agricultural systems see, table 12, p 33. in: Tyedmers, P. (D. Zeller, R. Watson, and D.and Pauly, Eds.) (2001) *Energy consumed by North Atlantic Fisheries*. In *"Fisheries Impacts on North Atlantic Ecosystems: Catch, Effort and National/Regional Datasets"*. Fisheries Centre Research Reports 2001 Vol 9 No. 3, pp. 12-34. (Tyedmers has published several very good papers and a PhD. on this.)

6. Estimates of British wheat yield 1200-1800 are from: J. S. Amthor. (1998) *Perspective on the relative insignificance of increasing atmospheric CO_2 concentration to crop yield*. Field Crops Research. Vol. 58, Issue 2, 4 August 1998, pp. 109-127.

7. Chen, Chun. (1997) *Developmental History Of Paddy Rice And Arid Agriculture In Ancient Chinese Civilization,* Agricultural Archaeology (86-3), pp. 51-53 (trans. by Elaine Wong & Aurora Zhang; ed. by E. Wong, Allison Craig, Bryan Gordon & Frank Bayerl)

If you want more agriculture references and data please ask.

Someone asked about what will happen if The Gulf Stream shuts down

The following notes are an attempt to answer the question about the climate effects of a shut down of the gulf stream. Be aware that I do not consider myself an expert (despite having studied oceanography etc. and having read many papers relating to this.) And that I worry that I am, like everyone, susceptible to confirmation bias. However, I think the following is useful.

The thermohaline circulation

Thermohaline is formed from a combination of two words: thermo - temperature and haline - salt.

The density of seawater depends on its temperature and salinity. Its density increases as its temperature falls and its salt content rises and water that is denser than the water below it sinks.

The currents that flow across the ocean floors originate where cold salty water sinks. Surface currents are driven by the wind that blows over the ocean. Together these two effects drive the ocean circulation which transport, heat energy, dissolved gas, and nutrients around the oceans. On average the wind blows parallel to the temperature gradients that exist between the tropics and the poles, between ice and water and between land and sea. The gulf stream / North Atlantic drift is part of such a wind and density-driven circulation that transports heat from the Gulf of Mexico northwards to high latitudes. The water in the gulf stream cools as it flows northwards and its salinity increases as wind-driven evaporation removes freshwater until in the high arctic it sinks and flows south along the ocean floor to the antarctic. We have known for a long time that the thermohaline circulation can (almost) shut down and that it has done so many times in the past when freshwater from melting ice sheets floods into the North Atlantic. The fresh meltwater dilutes the dense salty water that drives the circulation preventing it from sinking. The state of the circulation has a large impact on the climate of the Earth.

At present, the Gulf stream only transports about 15% of the heat that warms Europe. The rest is carried by the prevailing southwest wind. See [1] for a non-technical explanation and [2] for more detail.

1. Seager, R. (2008) Setting the record straight on Europe's mild winters. The Plantsman, Royal Horticultural Society, 7, Part 1 March, pp. 22-27

2. Seager, R, D. S. Battisti, J. Yin, N. Gordon, N. H. Naik, A. C. Clement and M. A. Cane (2000) Is the Gulf Stream responsible for Europe's mild winters? Quarterly Journal of the Royal Meteorological Society, 128(586): pp. 2563-2586.

There are two corollaries:

1. If the thermohaline circulation slows or shuts down in response to meltwater from the Greenland ice cap flooding into the north Atlantic as Greenland warms in response to climate change, a new ice age will not start. And, I suspect, that any cooling will quickly be overwhelmed by the accuimulating effects of climate change.

2. During the deglaciation at the end of the most recent ice age the shut down of the thermohaline circulation may have had a much larger effect on Europe's climate than it would today. With ice sheets still covering much of the northern hemisphere and the winter sea ice edge much further south than it is now, it may, as is suggested by computer modelling, have caused the prevailing SW wind the switch to a stronger westerly flow and shut off a large fraction of the heat transport to Europe. [3]

3. Eisenman, I, C. M. Bitz, and E. Tziperman. (2009) Rain driven by receding ice sheets as a cause of past climate change, Paleoceanography. vol. 24, PA4209.

See the following which describes how the earth deglacicated at the end of the last ice age:

Jeremy D. Shakun, Peter U. Clark, Feng He, Shaun A. Marcott, Alan C. Mix, Zhengyu Liu, Bette Otto-Bliesner, Andreas Schmittner & Edouard Bard. (2012) Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. Nature, 484. pp. 49-54

This is not to imply that shutting down part of the ocean circulation is a good idea!

The problem with geo-engineering and the need to think and calculate all the consequences

I talked about the problems of geo-engineering (which I fear we may have to try) in relationship to the suggestion that we farm kelp in 10% of the area of the worlds oceans and how if this is done in deep water a great deal of rope is needed which I suspect would lead to the extinction of the great whales by entaglement. It would also lead to an increase in plastic polution of the sea brcause fibres would be lost from the ropes as well as some of the ropes themselves. The problem of plastic polution could, in theory, be mitigated by replacing plastic with natural fibres. So I wanted to know what the costs, measured in land area, and consequences of this would be. I am writing about this because I find that the people proposing large scale projects rearly, if ever, do even the most simple sums to figure out the costs to the earth system of their ideas.

In 2016 production of man-made fibres was 70.315 million tonnes. Suppose we want to replace them with cotton, (or more likely a mixture of natural fibres,) then we will need to grow 70 million tonnes of cotton. Cotton has a yield of around 779 kg/ha. It follows that if we want to replace man-made fibres with cotton we will need to plant an area of land = 70,315,000,000/779 ha = 90,263,158 ha which is 5.92% of the world's cropland.

This implies changing 5.9% of the land area that is presently used for food crops to cotton production. I don't know if that's possible without doing a much more detailed analysis than I have done in this 'cartoon' estimate because while it's easy to calculate the area of agricultural land that would be needed it is harder to work if there is enough land with suitable soil and climate. Or if we can afford to take that land out of agricultural use because we are trading food for fibre production. If it is not possible to do this it might be possible to replace some man-made fibre with flax which has a higher yield and hence requires less land than cotton. Or we could replace some man-made fibres with wool because grazing animals e.g. sheep and alpaca, can graze on land that is not used for food crops, and occupy the ecological niche that the extinct megafauna used to fill. I also strongly advise that we make good quality clothes and keep and patch them for as long as possible.

We might want to do this in order to reduce the flow of micro-plastic fibres into the environment because they are accumulating in the bodies of most living things with as yet not fully understood consequences. What we do know is that some of the chemicals in plastics disrupt hormones and are significantly reducing the fertility of both humans and animals. E.g. Bisphenol A and Phthalates. The Orca who live in the waters of the west coast of Scotland are now infertile because they have accumulated these compounds in their bodies! (I strongly suspect these compounds are having other effects too! Think - "The Silent Spring")

Note: I am sure it is impossible to replace all man-made fibres with natural fibre because for some applications e.g. sailcloth and ropes made fibres are both stronger and more durable. But I think it is worth considering for clothing because that might reduce the impact that plastics are having on the environment.

I am far beyond fed up with reading about large scale projects that cannot, with any foreseeable near term technology, hope to solve our problems being advocated so I spoke about the impossibility of mining the moon and creating a human colony on mars.

Things that won't work: mining the Moon

I am in favour of space exploration and all the knowledge and benefits that it has brought us but I am not in favour of misleading the public into thinking we can solve our problems with technically impossible schemes.

Mining on the Moon

The Apollo program brought 382 kg of the Moon back at a 1973 cost of $25.4 billion which was 2.3% of the USA's GDP in 1969.

Let us assume that Moon rock contains the same amount of titanium as the Earth's crust, 0.56%. It follows that the six Apollo missions brought back a total of 382 x 0.0056 kg = 2,139 grams of Titanium at a cost of $12 million per gram. Bear in mind that anyone can pick up 382 kg of rock pretty much anywhere on Earth for free. If the returned rock were solid titanium then the cost was $66,490 per gram. For comparison, the price of titanium in 2014 was $6.20/kg so at current market prices it is necessary to reduce the cost of mining the Moon by a factor of two billion before it becomes economically attractive.

The fuel burned by the Apollo rockets contained 584,617 GJ of energy making Moon rock cost 1,530 GJ/kg (2,870 times the specific energy cost of producing titanium on Earth.) In collecting it the six rockets used by the Apollo program discarded 1,062 tons of material, some of it was left on the Moon, some is still in orbit and most of the rest fell in the ocean. All of it high-grade alloys. In other words, 2,780 kg of aluminium, titanium, Inconel were exchanged for every kg of rock. In material terms this is a very poor trade.

Reaction engines SARBRE engined spaceplane may, eventually, reduce these energy costs by a factor of 10 - 20, and economic costs by a factor of a hundred but that is not enough to make mining feasible.

Things that won't work: permanent 'colonies' on the Moon and Mars

To make any of the more ambitious manned space missions possible we need improvements in technology that deliver energy and cost savings of several orders of magnitude. The gains that have been made by using new materials, electronics and by reusing boosters are impressive and will reduce the costs of satellite launches and both manned and unmanned space exploration but they will not enable colonisation of the Moon or Mars. These places are utterly unlike anywhere people have colonised in the past. They cannot be reached by walking. They have no, or might as well have no, atmosphere, no liquid water and there is no food growing.

I think there are two scenarios:

The first scenario is a series of Apollo mission like visits, perhaps eventually leading to a semi-permanently manned base similar to the Antarctic research stations.

The first problem is the dust. On Earth dust is suppressed by moisture, bound by roots and perhaps most importantly ground and blunted by the actions of wind and water. On the Moon, it is sharp like the abrasives used for grit blasting. It caused the Apollo crews a lot of trouble, the longest they stayed on the Moon for was three days. Reading the reports from the missions leads me to suspect the dust would have forced them to abort their missions if they had tried to stay much longer.

"Mission documents from the six Apollo missions that landed on the lunar surface have been studied in order to catalog the effects of lunar dust on Extra-Vehicular Activity (EVA) systems, primarily the Apollo surface space suit. It was found that the effects could be sorted into nine categories: vision obscuration, false instrument readings, dust coating and contamination, loss of traction, clogging of mechanisms, abrasion, thermal control problems, seal failures, and inhalation and irritation. Although simple dust mitigation measures were sufficient to mitigate some of the problems (i.e., loss of traction) it was found that these measures were ineffective to mitigate many of the more serious problems (i.e., clogging, abrasion, diminished heat rejection). The severity of the dust problems were consistently underestimated by ground tests, indicating a need to develop better simulation facilities and procedures." [38]

"Space suit anomalies caused by lunar dust created problems for the Apollo program. During Apollo 12 wrist and suit hose locks became difficult to operate, suit fabric was abraded and leak rates increased. The Apollo 14 crew reported helmet visor scratches that decreased visibility. The Apollo 15 crew was hampered by difficulty in connecting and disconnecting PLSS PGA connection and disconnection. During Apollo 16 lunar operations, dust in zippers led to difficult operation; wrist ring pull connectors were covered with dust, degrading mobility; PLSS RCU displays were abraded and could not be read; and dust in helmet visor mechanisms resulted in over visors that would not retract. The Apollo 17 crew reported stiff glove connectors, stickiness in helmet visor retraction, and reduced visibility due to scratches and dust accumulation on visors." [39]

"Dust – I think probably the most aggravating, restricting facets of lunar surface explorations is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and it's restrictive friction-like action to everything it gets on. For instance, the simple large tolerance mechanical devices on the Rover began to show the effects of dust as the EVAs went on. By the middle or end of the third EVA , simple things like bag locks and the lock which held the pallet on the Rover began not only to malfunction but to not function al all. They effectively froze. We tried to dust them and bang the dust off and clean them, and there was just no way. The effect of dust on mirrors, camera, and checklists is phenomenal. You have to live with it but you're continually fighting the dust problem both outside and inside the spacecraft. Once you get inside the spacecraft, as much as you dust yourself, you start taking off the suits and you have dust on your hands and your face and you're walking in it. You can be as careful in cleaning up as you want to, but it just sort of inhabits every nook and cranny in the spacecraft and every pore in your skin." [40]

I don't know how the dust on Mars compares with that on the Moon. I suspect it may not be so bad because Mars has some atmosphere which must have weathered the 'soil' and partially melted and hence rounded micro meteorites falling through it.

The Moon has no atmosphere and Mars very little compared with Earth. Its mean surface pressure is 0.60 kPa. The same as 35 km (22 miles, 116,000') above Earth's surface. Which has two effects. You have to wear a space suit because even on Mars you might as well be in a hard vacuum, and with no atmosphere there is no, (very little), convection so it is much harder to dissipate heat than it is on Earth.

The surface gravity of Mars is 37% of Earth's and the Moon 16%. I'm not sure what harm that will do to any inhabitants. I suspect it may, at best, cause long term physiological changes that will make returning to Earth difficult. And if people are ever born on these worlds then they may not be able to visit Earth at all.

The second scenario is the establishment of a permanent colony of a large enough population to be genetically viable and able to maintain itself. This will require, I guess, around a million people. The logic behind this plan being that if life on Earth is wiped out then humans will survive. To make this plan work we have to be able to grow enough food and manufacture everything we need. That requires we construct a vary large habitat. It must be pressurised either as a 'greenhouse' on the surface or buried and artificially lit. It must also be large enough to sustain a viable ecology. It will have to be assembled in a hard vacuum by people wearing pressure suits or by robots. It also has to be shielded against high energy particles and radiation. (The Earth's atmosphere and magnetosphere does this for us for free.) Power has to be generated, metals smelted and worked, lubricants and plastics or their equivalents synthesised on a planet with no oil. I suspect industrial scale smelting and metal working will be difficult because it will be hard to dissipate the heat and fumes in a closed habitat in a vacuum. I will stop now. These are a very few of the real engineering problems that have to be solved for a colony to succeed.

Some of these problems were discussed in the nineteen seventies in connection with the, Gerard K. O'Neil space Colonies and by Molly Gloss in her beautifully written novel, *The Dazzle of Day.* I recommend both of these as good starting places for anyone interested in the problems of creating such a self contained habitat.

We are already slowly exploring the Moon and Mars using robot landers, which will continue to become more capable. Do we need to go ourselves.

I can see the value of a manned deep space mission, perhaps a Mars orbit and return, to allow humans to see the Earth from very far way. I hope that might frighten some sense into us.

I am absolutely certain the only way to ensure the survival of humanity is for us to find a way to continue to live on Earth without further damaging it. If we can do that then in time we may develop the technology to make outpost colonies possible. Though I would rather stay on Earth, it is the only planet with forests, oceans and kelp.

1. Congress, House of Representatives, Committee on Science and Astronautics (1973) 1974 NASA Authorization Hearings (Hearing on H. R. 4567). Washington, D. C, 93rd Congress, first session. OCLC 23229007.

2. NASA (1968) *Saturn V Flight Manual*. SA-503, NASA, George C. Marshall Space Flight Center.

3. Monika Gisler and Didier Sornette, *'Bubbles in Society' The Example of the United States Apollo Program,* arXiv:0806. 0273v1

4. James R. Gaier. *The Effects of Lunar Dust on EVA Systems During the Apollo Missions*. NASA/TM—2005-213610

5. Sandra A. Wagner. *The Apollo Experience Lessons Learned for Constellation Lunar Dust Management*. NASA/TP-2006-213726

6. Gene Cernan. *Apollo 17 Technical Debrief*. (Apollo 17 was the last mission and longest mission. They stayed for 3 days.)

7. Bardi, Ugo. (2008) *The Universal Mining Machine*. The Oil Drum, http://europe.theoildrum.com/node/3451
This is about the energy cost of mining and the problem with mining low grade ores, and in the limit extracting elements from common rock.

Finally someone asked me what I think will happen

The short answers are I don't know and collapse.

A longer answer is that a combination of population growth coupled to climate change will render the world ungovernable and then our civilisation will collapse. But this is not interesting, what is interesting is how to avoid or delay the collapse and to minimise damage to the earth system.

I am sure we have no choices and only a chance of rescuing our civilisation and holding onto a more or less intact biosphere. The laws of physics allow no other option. To do this we have to reimagine the way in which we think about ourselves and our place on earth.

Here is an outline of the beginning of a plan

I am assuming that all of the following are implemented over a thirty-year planned transition period in order to keep the needed material and energy flows, (e.g. glass manufacture for solar panels), at a feasible level of a few per cent of present world production.

• Empower women, give them equal opportunities, an equal voice in decision making, equal respect for equal work, and pay the same wage for the same work. I believe this to be the single most important and needed change that must be made.

• Reduce population everywhere, in all countries, by voluntary birth control. We should aim for one child per couple, some couples will have more children, some none. I hate this too but the alternative is for at least several billion people to die.

• Plan ways to adapt to and accommodate future migrations
• Plan ways to protect vulnerable areas from the effects of high humidity and temperature and from storms
• Plan retreat from areas that will be flooded

• Improve agriculture: We need to adopt agroecological and agroforestry practices, (which are already common and feeding 80% of the population except in the developed world!) Historical climate data suggests that stopping meat production (removing cattle from the agricultural system) may provide a way to cool the planet. If we are lucky and if we also reafforest every bit of land we can spare from food production it might provide a way back to the cold climate of the past. This will require a larger, but not much larger, agricultural workforce. A doubling in the number of farm-workers only requires an additional 1% - 1 in 100 of the population, so it should be easy to find enough workers. The problem is only how to pay them a living wage, which implies we will have to pay more for food or subsidise it.

• Do less with less
• Design appliances and vehicles for easy repair and disassembly for recycling
• Reassess infrastructure development to minimise environmental and energy cost
• Reduce the amount of shipping and travel to a minimum
• More - much more - public transport

• We need to stop flying, imagine a ninety per cent reduction in air travel. Fly only when it is absolutely necessary. The answer is not to 'carbon offset' and carry on as usual. Newspapers that contain articles about climate change and environmental degradation continue to run travel articles about where to fly to. Stop. Join the dots up, think, but above all stop.

• Transport must be made more energy and resource-efficient. The use of lightweight electric cars, electric bicycles, and bicycles are probably the only technologies that reality will permit. [Note: In the long term it may be technically possible to make aircraft genuinely climate neutral, but this will, if it is possible, take decades and while it will allow more flying than is possible while we 'hunker down' in survival mode, it will not allow unlimited flying. We will still have to moderate what we do.]

• Insulate houses. This has the potential to improve the quality of life of a large number of people and if done to a high standard eventually reduce world energy use by a third. It will also mean that everyone's heating and cooling bills will be reduced by 98%, everyone will be warm, and many fewer people will get ill in cold damp climates, and it will be much easier to keep buildings comfortably cool in the tropics. This energy-saving is equivalent to taking all vehicles off the road and it will create work. Why would we not want to do this?
• Design and alter housing to maximise habitability
• Eventually as the population falls we will need to take down buildings to stop the materials they contain from leaking into the environment. This will need a very large labour force who must be fed and clothed.

• A thirty-year transition to a global renewable (mainly solar and wind) energy supply
• Continue research to develop safe nuclear power (fusion, energy amplifier etc.) to find out if they are possible. Then we can decide whether to use them or not.

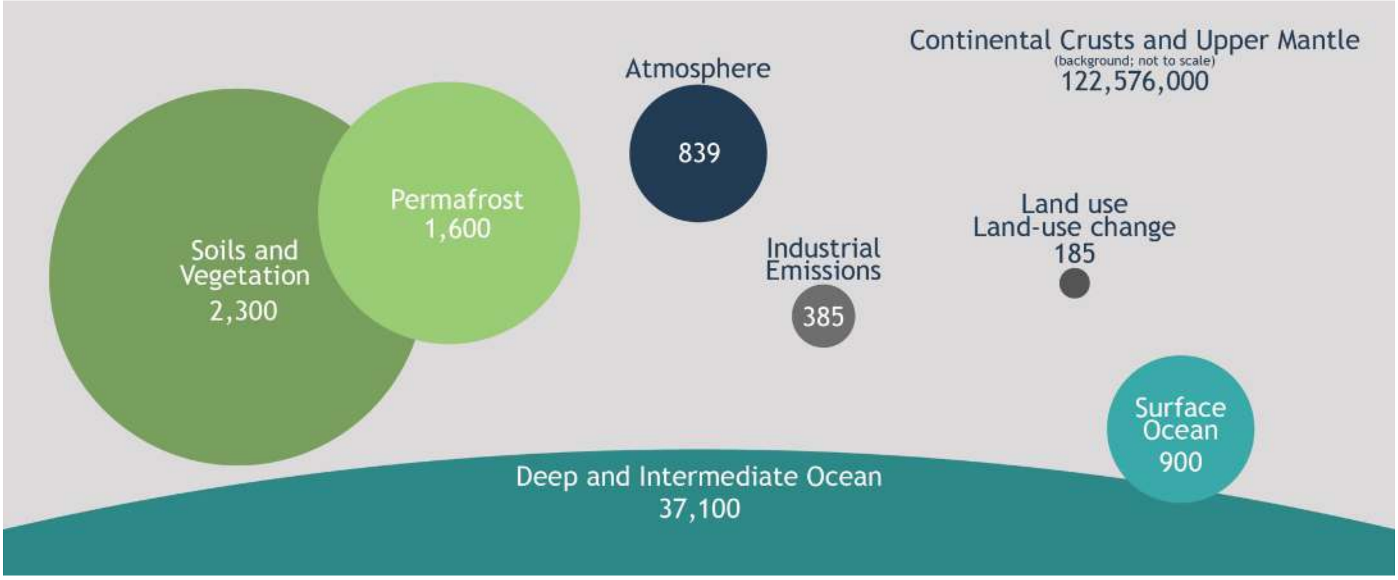
• We need to clean the plastic we have littered the world with and we need to do it now. We cannot afford to wait until we have invented a machine to do it for us. This will require work and the workers will need paying.

Such a plan delivers the following benefits:

- Upgraded, insulated, housing for everyone
- A 98% reduction in heating and cooling bills
- A 100% reduction in the number of people whose lives are shortened by air pollution from burning fossil fuels (A rough estimate shows that 253 million lives have been shortened, many by a decade or more, during the 20th century due to the health effects of burning fossil fuels.)
- A secure food supply
- Safer transport and with that a reduction in road deaths of up to 1.3 million a year
- An end to war and with that 370,000 lives saved every year
- That we leave a rich, complex, beautiful planet for our children and their children
- That we hold onto the near miraculous benefits of things like medical care, anaesthesia, and education.

I did not conjure this plan from thin air. It is the result of detailed calculation and analysis. For example in working out how much energy renewable and non-renewable power sources generate compared with the energy that is used to construct the power source (station) I plotted a graph that shows how this ratio has improved over time for solar panels. There are 27 points plotted, each of these points is taken from a separate paper or report. I have done similar detailed calculations for transport, agriculture, housing, and for the energy and material flows that will be required to make a transition over a thirty years period to a perhaps, just, stable transition to sustainability.
This still falls far short of a full systems dynamic or/and numerical forecast model for our planet. To implement that a large research group and probably a collaboration between many groups comparable to the work of the IPCC will be needed.

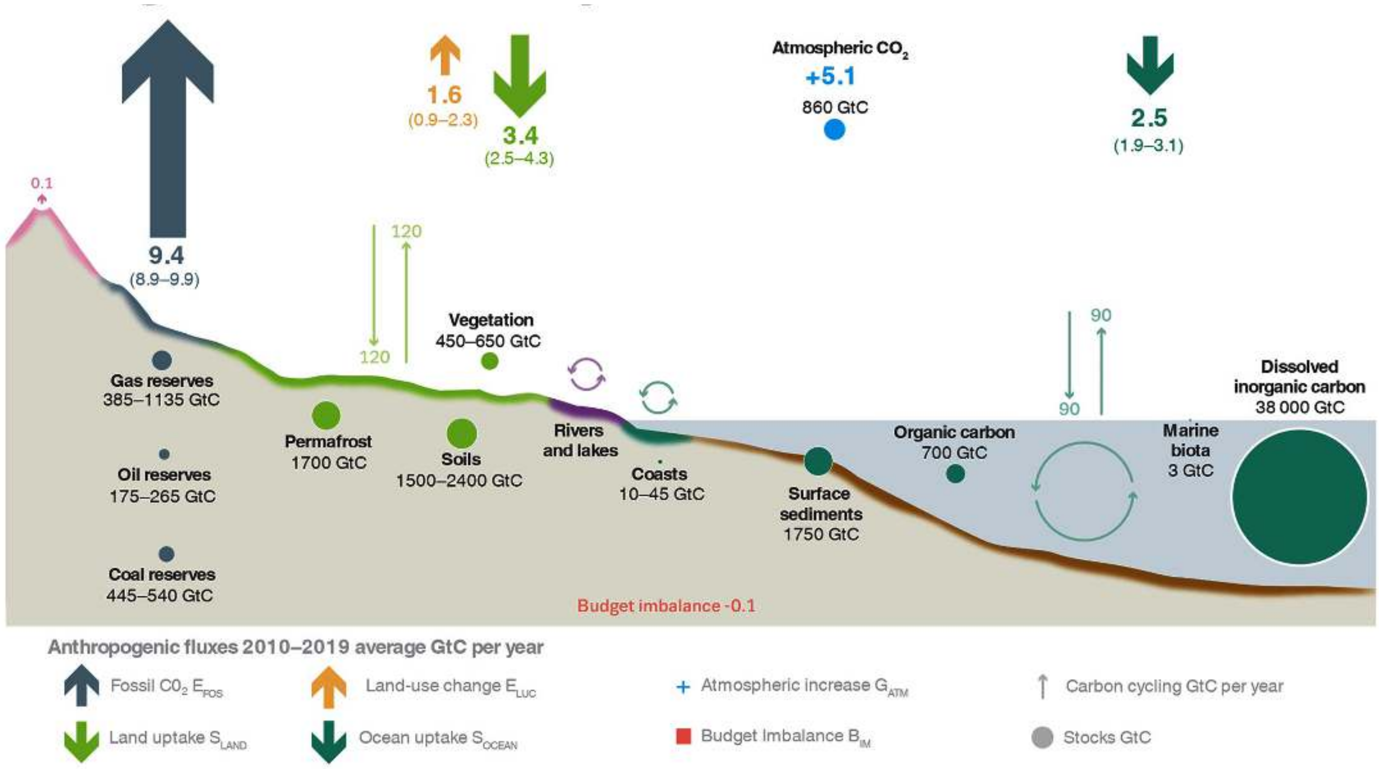
Appendix: The global stores and flows of carbon in the Earth system



The approximate relative sizes (in gigatonnes) of the main storage pools of carbon on Earth. Cumulative changes (thru year 2014) from land use and emissions of fossil carbon are included for comparison.

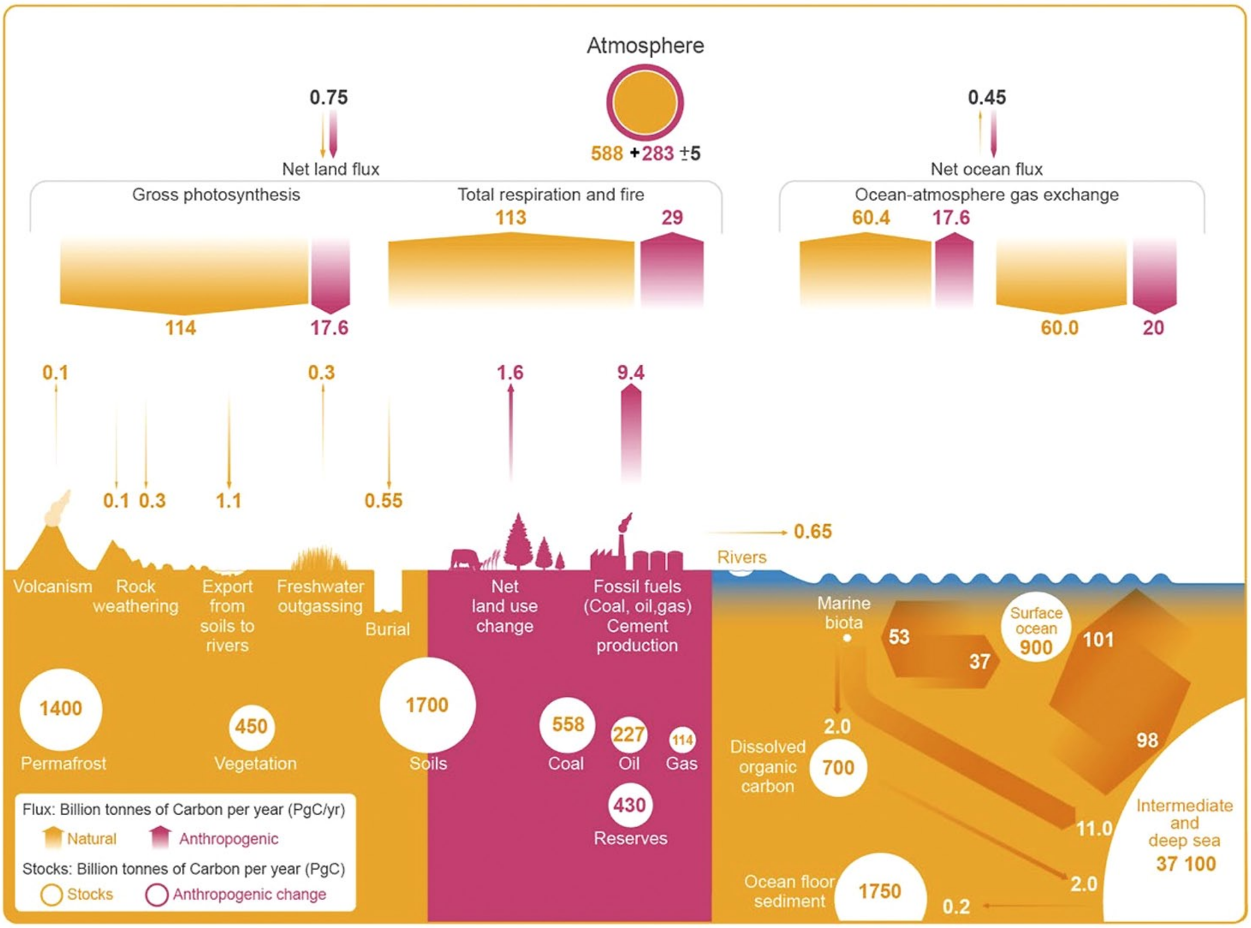
This image summarizes the relative sizes of the largest "stocks" or "pools" of carbon storage on the earth. The atmosphere is one carbon stock, and contains 839 gigatons of carbon (Gt C), mainly in the form of carbon dioxide (CO_2). The Earth's largest carbon stock is found within the continental crusts and upper mantle of the Earth (122,576,000 Gt C), a large portion of which is sedimentary rock formed over millions of years (Mackenzie and Lerman 2006). Oceanic carbon is the next largest stock (37,100 Gt C). More than 95 percent of oceanic carbon is mainly present in the form of inorganic dissolved carbon, while only 900 Gt C is available for exchange in the surface ocean. Plants take up carbon through photosynthesis, and this carbon is subsequently allocated above- and below ground, contributing to the global vegetation stock. Globally, forests account for 92 percent of all terrestrial biomass, storing approximately 400 Gt C (Pan et al. 2013). Soils store approximately 1,325 Gt C in the top 1 meter of soil alone and 3,000 Gt C in total when soil at deeper depths is included, although large uncertainties are introduced due to unconstrained soil properties (such as peat bulk density and estimates of permafrost at depth, among others) (Köchy et al. 2015). In addition, permafrost (frozen soil) stores a large pool of carbon that is climatically protected from decomposition (Trumbore 2009; Schmidt et al. 2011), although more and more of this pool is becoming available as the average global temperature rises (Schuur et al. 2015, Guido et al. 2016). Carbon emissions to the atmosphere from human activity (predominantly the result of fossil fuel combustion and land-use change) have been rising since the industrial revolution. Fossil fuel combustion has contributed nearly 385 (+/- 20) Gt C since the industrial revolution up to year 2015, or about 70 percent of the total anthropogenic contribution since 1750 (570 +/- 70 Gt C) (Canadell and Schulze 2014). Land use and land-use change constitute the remaining 30 percent of emissions for the same time period, or 185 (+/- 65)Gt C.

From: Kayler, Z., Janowiak, M., Swanston, C. (2017). "The Global Carbon Cycle". Considering Forest and Grassland Carbon in Land Management. General Technical Report WTO-GTR-95. United States Department of Agriculture, Forest Service. pp. 3–9.



Aanthropogenic p**erturbation of the global carbon cycle**

Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2010–2019. See legends for the corresponding arrows and units. The uncertainty in the atmospheric CO_2 growth rate is very small (±0.02 GtC yr^{-1}) and is neglected for the figure. The anthropogenic perturbation occurs on top of an active carbon cycle, with fluxes and stocks represented in the background and taken from Ciais et al. (2013) for all numbers, with the ocean gross fluxes updated to 90 GtC yr^{-1} to account for the increase in atmospheric CO_2 since publication, and except for the carbon stocks in coasts which is from a literature review of coastal marine sediments (Price and Warren, 2016).
Cement carbonation sink of 0.2 GtC yr^{-1} is included in the fossil fuel emission (E_{FOS}).



The global carbon cycle (2010-2019)

Yellow arrows represent annual carbon fluxes (in PgC yr-1) associated with the natural carbon cycle estimated for the time prior to the industrial era, around 1750.
Pink arrows represent anthropogenic fluxes averaged over the period 2010–2019. The rate of carbon accumulation in the atmosphere is equal to net land-use change emissions, including land management (called LULUCF in the main text) plus fossil fuel emissions, minus land and ocean net sinks (plus a small budget imbalance, Table 5.1). Circles with yellow numbers represent pre-industrial carbon stocks in PgC.
Circles with pink numbers represent anthropogenic changes to these stocks (cumulative anthropogenic luxes) since 1750. Anthropogenic net fluxes are reproduced from Friedlingstein et al., (2020). The relative change of gross photosynthesis since pre-industrial times is based on 15 DGVMs used in Friedlingstein et al., (2020). The corresponding emissions by Total respiration and fire are those required to match the net land flux, exclusive of net land-use change emissions which are accounted for separately. The cumulative change of anthropogenic carbon in the terrestrial reservoir is the sum of carbon cumulatively lost by net land use change emissions, and net carbon accumulated since 1750 in response to environmental drivers (warming, rising CO_2, nitrogen deposition). The adjusted gross natural ocean-atmosphere CO_2 flux was derived by rescaling the value in figure 1 of (Sarmiento and Gruber, 2002) of 70 PgC/yr by the revised estimate of the bomb 14C inventory in the ocean. The original bomb 14C inventoy yielded an average global gas transfer velocity of 22 cm/hr; the revised estimate is 17 cm/h leading to 17/22 x 70 = 54. Dissolved organic carbon reservoir and fluxes from (Hansell et al., 2009).
Dissolved inorganic carbon exchanges between surface and deep ocean, subduction and obduction from (Levy et al., 2013) Levy et al. 2013. Export production and flux from (Boyd et al., 2019). NPP and remineralisation in surface layer of the ocean from (Kwiatkowski et al., 2020; Séférian et al., 2020). Deep ocean reservoir from (Keppler et al., 2020). Note that the mass balance of the two ocean carbon stocks 24 surface ocean and intermediate and deep ocean includes a yearly accumulation of anthropogenic carbon (not shown). Fossil fuel reserves are from (BGR, 2019); fossil fuel resources are 11,490 PgC for coal, 6,780 PgC for oil, and 365 PgC for natural gas. Permafrost region stores are from (Hugelius et al., 2014; Strauss et al., 2017; Mishra et al., 2021) (see also Box 5.1) and soil carbon stocks outside of permafrost region from Batjes, (2016); Jackson et al., (2017). Biomass stocks (range of seven estimates) are from Erb et al., (2018). Sources for the fluxes of the continuum land-to-ocean are provided in main text and adjusted within the ranges of the various assessment to balance the budget (section 5.2.1.5).

IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.

References and notes

These references include, books, scientific papers, and notes explaining in outline why they are relevant. The books are all paperbacks written for the general public, they assume no previous knowledge and are interesting and easy to read. I have highlighted these books in green.

There really is no point in talking about anything unless the state of the earth system as a whole is considered

Fifty years ago computers were slow and had very little memory and if you had a question then you had to write your own computer program to answer it. You could not use someone else's computer program as an oracle, you had to find your own answers. The Apollo missions had reached the moon and shown us the earth as a blue cloud bound ball of sunlit half-darkness hung in an infinite void and a small group of engineers set out to explore all the possible futures of a technological civilisation living on a finite world. They published their results as *The Limits to Growth*. They did not, as is often claimed, forecast that industrial society would inevitably collapse but rather tried to map the factors that led to stability or to collapse. The world model of *The Limits to Growth* is not like a computer program written to calculate the path taken by a kicked football, which given the air density, the exact shape of the ball, the force and point of impact of the players foot on the ball, the air pressure in the ball, and the wetness, and height of the grass on the pitch will accurately predict the path the ball follows. Instead it tells only that the ball will follow a parabolic path, that the path a ball given spin follows will bend to the left or right depending on its direction of spin, and that there are definite, though approximate limits on how high and far a football can be kicked. It is exactly because the world model of *The Limits to Growth* is so general that the patterns it maps are so certain. Their simulation showed that:

1. A stable civilisation is only possible if the population of the earth is limited and growth in resource use stops
2. Any attempt to continue business as usual where population and resource use grow unchecked leads to collapse
3. The use of high technology to enable continued growth can delay but cannot prevent collapse. [1]

In 1973 when *The Limits to Growth* was published the authors found that it was possible for our civilisation to choose to follow a path that led to stability. Ten years later when they published their first ten yearly update to *The Limits to Growth* they found that the collapse of our civilisation is unavoidable so that now the only question left to answer is something like, "*How should we live with grace in a dying world?"*

Their model did not include climate change but a more general representation of pollution and hence environmental degradation. For the purposes of mapping the future, this does not matter. For us, it does because we now have a working understanding good enough to foresee some of the things that will happen during the next few decades.[2, 3, 4, 5, 6, 7, 8, 9]

I still hope that if we are lucky and if humanity can work together, as we have never done before, we can prevent collapse and the loss of life that will follow it or at worst leave some of the staggering and strange richness of the earth intact in the ruins of our civilisation.

1. The Limits to Growth and its prehistory

Read the prehistory first: https://www.technologyreview.com/s/538561/the-many-careers-of-jay-forrester/

A PDF copy of The Limits to Growth can be downloaded here: http://www.donellameadows.org/wp-content/userfiles/Limits-to-Growth-digital-scan-version.pdf

2. Peter Wadhams, (2017), *A Farewell to Ice, A Report from the Arctic*, Penguin.
Peter Wadhams home page is at: https://www.damtp.cam.ac.uk/user/pw11/

His book contains a clear explanation of how greenhouse gases warm the earth and of the long term Earth systems climate sensitivity which has been estimated as + 4 degrees by 2100 even if the concentration of atmospheric CO_2 stays at 410 ppm! (The IPCC only estimates the immediate temperature change induced by increasing the concentration of greenhouse gases in the atmosphere, The Transient Climate Response and The Equilibrium Climate Sensitivity, see below. The problem with this that this short term warming causes changes (like melting of sea ice that reduces the amount of sunlight that is reflected by the earth) that feedback increasing the long term equilibrium temperature of the earth.

The sources for the Earth systems climate sensitivity are from:

3. Reference 3 in chapter 4 of *A Farewell to Ice*
4. http://www.apollo-gaia.org/SCBContributions/Wadhams-140606.html
5. http://www.apollo-gaia.org/sensitivitycarbonbudget.html
6. For climate sensitivity and the definition of the Radiative Damping Coefficient see, Previdi M, Liepert BG, Peteet D, Hansen J, Beerling DJ, Broccoli AJ, Frolking S, Galloway J N, Heimann M, Le Quere C, Levitus S, Ramaswamy V. 2013. Climate sensitivity in the Anthropocene. Q. J. R. Meteorol. Soc. 139 : 1121 – 1131. DOI:10.1002/qj.2165

Note on the IPCC definitions of climate sensitivity

The following was written just before the release of AR6 so that some of this is now out of date.

The Transient Climate Response (TCR)

Is the near term temperature rise defined as *"is the change in the global mean surface temperature, averaged over a 20-year period, centred at the time of atmospheric carbon dioxide doubling, in a climate model simulation" in which the atmospheric CO_2 concentration is increasing at 1% per year"*

In Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. p. 1451.

The Equilibrium Climate Sensitivity (ECS)

Is the long-term temperature rise (equilibrium global mean near-surface air temperature) that is expected to result from a doubling of the atmospheric CO_2 concentration. It is a prediction of the new global mean near-surface air temperature once the CO_2 concentration has stopped increasing and most of the feedbacks have had time to have their full effect. Reaching an equilibrium temperature can take centuries, or even millennia, after CO_2 has doubled.
By definition, equilibrium climate sensitivity does not includes feedbacks that take millennia to emerge, such as long-term changes in Earth's albedo due to changes in ice sheets and vegetation. It does include the slow response of the deep ocean warming up, which also takes millennia, and as such ECS doesn't reflect the actual future warming that would occur if CO_2 is stabilized at double pre-industrial values
The IPCC Fifth Assessment Report (AR5) stated that *"there is high confidence that ECS is extremely unlikely to be less than 1 °C and medium confidence that the ECS is likely between 1.5 °C and 4.5 °C and very unlikely greater than 6 °C"*. The long time scales involved with ECS make it arguably a less relevant measure for policy decisions around climate change.

IPCC First Assessment Report (1990)
Equilibrium climate sensitivity 1.5 and 4.5 °C

The IPCC supplementary report (1992) saw *"no compelling reason to warrant changing"*

IPCC Second Assessment Report said that *"No strong reasons have emerged to change [these estimates]"*

IPCC Third Assessment Report retained the estimate of the ECS given in the first assessment report

IPCC Fourth Assessment Report (AR4) (2007)
Equilibrium climate sensitivity 2 to 4.5 °C

IPCC Fifth Assessment Report (AR5) (2013)
Equilibrium Climate Sensitivity 1.5 to 4.5 °C
Equilibrium Climate Sensitivity 1 °C - 6 °C

IPCC Sixth Assessment Report (AR6) (To be published in 2022)

Transient climate response from 2.0 °C
Equilibrium Climate Sensitivity 3.7 °C

Peter Wadhams and David Wasdell have estimated the earth system sensitivity and write that, *"They based their assessment on the effects of the known fast feedbacks like increase in water vapour with rising temperature, reduction in reflection from shrinking areas of sea-ice, and changes in cloud effects. They estimated that the global feedback system amplified the effects of* CO_2 *on its own by some 3.1 times. "Climate Sensitivity" is defined as the change in equilibrium temperature correlated with a doubling in concentration of atmospheric* CO_2*, so their calculations yielded a sensitivity value of around 3°C. The current ensemble of computer models on which the IPCC reports are based still uses this "fast-feedback sensitivity" to predict future change in temperature. It is immediately clear that this sensitivity value is consistent with the prediction of a 2°C rise at a* CO_2 *concentration of 440 ppm."*

"Another outcome of replacing the fast feedback sensitivity with the whole Earth System Sensitivity concerns the projected end-of-century temperature response to the current set of international commitments to reduction in CO_2 *emissions. With an expected total cumulative carbon emission of around 2000 Gt C, the IPCC SPM indicates a transient temperature response of around 4°C. The ESS corrects this to around 10°C, with the extension to full equilibrium response of more like 15 °C. An ice-free world and a sea-level rise of around 60 metres are in prospect."*

7. James Hanson, (2011), *Storms of my Grandchildren,* Bloomsbury

James Hanson's home pages is at: http://www.columbia.edu/~jeh1/

James E. Hansen points out that the estimates for sea level rise published by the IPCC are too low.

Direct testimony of James E. Hansen, before the Iowa Utilities Board re: Interstate Power and Light Company, Docket No. GCU-07-1

He wrote, *"The Intergovernmental Panel on Climate Change (IPCC, 2007) calculated a sea level rise of only 21-51 cm by 2095 for "business-as-usual" scenarios A2 and A1B, but their calculation included only thermal expansion of the ocean and melting of alpine glaciers, thus omitting the most critical component of sea level change, that from ice sheets. The IPCC noted the omission of this component in its sea level projections, because it was unable to reach a consensus on the magnitude of likely ice sheet disintegration. However, much of the media failed to note this caveat in the IPCC report."*

(James Hanson is a climate scientist who ended his career as head of NASA's Goddard institute for space sciences where he was responsible for earth observation.)

8. Eun-Soon Im, Jeremy S. Pal, Elfatih A. B. Eltahir. (2017) *Deadly heat waves projected in the densely populated agricultural regions of South Asia,* Science Advances, 2 August 2017.

9. Steven C. Sherwooda and Matthew Huber. (2010) *An adaptability limit to climate change due to heat stress*, PNAS, May 25, 2010, Vol. 107, no. 2.

The physicist Enrico Fermi asked why in a cosmos that contains an uncountable number of stars, some of which have planets in orbit around them, (which we know because we have seen them), there are no aliens. (This is the Fermi paradox.) The evolution of life, the ways in which it shaped the earth, literally terraforming it, and was in turn shaped by the sun, earth, moon system. It's survival through many cataclysms, some of which were caused by the interaction of life itself with the earth system leads me to wonder if life is very rare, perhaps so rare that the earth is the only world in the cosmos inhabited by conscious creatures.

Definition of seaweed and how little we knew about its distribution and abundance until very recently

10. Bellamy D. & Whittick A. (1968) *Operation Kelp II*. Triton. February 1968.
Until very recently little was known about distribution and abundance of seaweeds. This led David Bellamy to set up a baseline kelp survey with the help of the BSAC in 1967/8

The brothers Eugene and Howard Odum wrote the first ecology textbook in 1953, *Fundamentals of Ecology,* the discipline's only textbook for more than a decade!

A food web that contains seaweed

11. James A. Estes. (2016) *Serendipity, An Ecologist's Quest to Understand Nature*. University of California Press.

12. Jane Lubchenco. (2016) Ecology: The sea-otter whisperer, Nature, 533. pp. 318-319. https://www.nature.com/articles/533318a

13. Lucy Sherriff, (2021) Climate Solutions, *The scientists fighting to save the ocean's most important carbon capture system*, Washington Post, July 5th 2021. https://www.washingtonpost.com/climate-solutions/2021/07/05/kelp-forests-destroyed-sea-urchins/

The above leads to:

14. Krause-Jensen D, Lavery P, Serrano O, Marba` N, Masque P, Duarte CM. (2018) *Sequestration of macroalgal carbon: the elephant in the Blue Carbon room*. Biol. Lett. 14: 20180236. http://dx.doi.org/10.1098/rsbl.2018.0236 https://royalsocietypublishing.org/doi/pdf/10.1098/rsbl.2018.0236

Note on the blind watchmaker.

William Paley wrote, *"In crossing a heath, suppose I pitched my foot against a stone, and were asked how the stone came to be there; I might possibly answer, that, for anything I knew to the contrary, it had lain there forever: nor would it perhaps be very easy to show the absurdity of this answer. But suppose I had found a watch upon the ground, and it should be inquired how the watch happened to be in that place; I should hardly think of the answer I had before given, that for anything I knew, the watch might have always been there. ... There must have existed, at some time, and at some place or other, an artificer or artificers, who formed [the watch] for the purpose which we find it actually to answer; who comprehended its construction, and designed its use. ... Every indication of contrivance, every manifestation of design, which existed in the watch, exists in the works of nature; with the difference, on the side of nature, of being greater or more, and that in a degree which exceeds all computation."*

Paley, William (1802), *Natural Theology: or, Evidences of the Existence and Attributes of the Deity*, London: J. Faulder

Richard Dawkins, (1986) *The Blind Watchmaker: Why the Evidence of Evolution Reveals a Universe without Design*, Penguin Books.

(I do not know if such a deity exists, and suspect that this is unknowable, so that in this talk I am playing with the idea of a blind watchmaker, knowing that I do not and can not say anything about the existence of a deity.)

Carbon sink

15. Freeman Dyson, From Eros to Gaia. Pantheon Books. 1992. There is one chapter about the mystery of (the then) poorly quantified carbon fluxes in the biosphere.

16. D. Krause-Jensen, C.M. Duarte, *Substantial role of macroalgae in marine carbon sequestration,* Nat. Geosci., 9 (2016), pp. 737-742

We propose two main modes for the transport of macroalgae to the deep ocean and sediments: macroalgal material drifting through submarine canyons, and the sinking of negatively buoyant macroalgal detritus. A rough estimate suggests that macroalgae could sequester about 173 TgC yr^{-1} (with a range of 61–268 TgC yr^{-1}) globally. About 90% of this sequestration occurs through export to the deep sea, and the rest through burial in coastal sediments. This estimate exceeds that for carbon sequestered in angiosperm-based coastal habitats. 173 million tonnes of carbon per year = 173 X 3.667 = 634 million t CO_2 / y

17. Grall, J.; Hall-Spencer, J.M. (2003). *"Problems facing maerl conservation in Brittany"* Journal of Aquatic Conservation: Marine and Freshwater Ecosystems. 13: 55–64.

18. Chung, I. K.; Beardall, J.; Mehta, S.; Sahoo, D.; Stojkovic, S. (2011). *"Using marine macroalgae for carbon sequestration: a critical appraisal"*. Journal of Applied Phycology. 23 (5): 877–886. doi:10.1007/s10811-010-9604-9

Marine photosynthesis accounts for 54-59 Gt C/year which is 50% of the total primary productivity of the planet
Algal beds and reefs of 2.5 kg per m^{-2} per year net primary production

A digression to phytoplancton

19. Behrenfeld, Michael J. (2014). *"Climate-mediated dance of the plankton"*. Nature Climate Change. 4 (10): 880–887.

Chalk

Chalk was formed in the Cretaceous, between 99 and 65 million years ago. It was deposited on extensive continental shelves at depths between 100 and 600 metres (330 and 1,970 ft), during a time of nonseasonal (likely arid) climate that reduced the amount of erosion from nearby exposed rock. The lack of nearby erosion explains the high purity of chalk. The coccolithophores, foraminifera, and other microscopic organisms from which the chalk came mostly form low-magnesium calcite skeletons, so the sediments were already in the form of highly stable low-magnesium calcite when deposited.

Coccolithophores are of particular interest to those studying global climate change because as ocean acidity increases, their coccoliths may become even more important as a carbon sink

Farming seaweed

20. *Seaweed Chronicles: A World At The Waters Edge,* Susan Hand Shetterly, Algonquin Books, (2018)

21. Michéal Mac Monagail, Lynn Cornish, Liam Morrison, Rita Araújo & Alan T. Critchley (2017) *Sustainable harvesting of wild seaweed resources*, European Journal of Phycology, 52:4, 371-390, DOI: 10.1080/09670262.2017.1365273

This contains a useful and interesting review of the methods, history, and problems associated with seaweed harvesting

The total global production of seaweed was 28.5 million tonnes and 800,000 t of seaweed is harvested annually from natural beds.

22. Sondak, C. F. A., Ang, P. O., Beardall, J. et al. *Carbon dioxide mitigation potential of seaweed aquaculture beds* (SABs). J Appl Phycol 29, 2363–2373 (2017). https://doi.org/10.1007/s10811-016-1022-1

In 2014, the total annual production of Asian-Pacific seaweed aquaculture beds surpassed 2,610,000 t dry weight. Total carbon accumulated annually was more than 0.78 million t y^{-1}, equivalent to over 2.87 million t CO_2 y^{-1}. [Authors note: I am wary of the claim about carbon dioxide accumulation because: 1. These constructing and operating these farms consumes energy and emits carbon as does transporting the seaweed to market so counting only the weight of carbon contained in the seaweed accounts for only part of a more complex mass balance. 2. The seaweed is then consumed and the carbon it contained is released back into the environment.

23. Antoine de Ramon N'Yeurt, David P. Chynoweth, Mark E. Capron, Jim R. Stewart, Mohammed A. Hasan, *Negative carbon via Ocean Afforestation*, Process Safety and Environmental Protection, Volume 90, Issue 6, November 2012, Pages 467-474

A mass balance has been calculated from known data and applied to produce a life cycle assessment and economic analysis. This analysis shows the potential of Ocean Afforestation to produce 12 billion tons per year of biomethane while storing 19 billion tons of CO_2 per year directly from biogas production, plus up to 34 billion tons per year from carbon capture of the biomethane combustion exhaust. These rates are based on macro-algae forests covering 9% of the world's ocean surface, which could produce sufficient biomethane to replace all of today's needs in fossil fuel energy, while removing 53 billion tons of CO_2 per year from the atmosphere, restoring pre-industrial levels. This amount of biomass could also increase sustainable fish production to potentially provide 200 kg/yr/person for 10 billion people. Additional benefits are reduction in ocean acidification and increased ocean primary productivity and biodiversity.

NOTE! Peter Liss at the University of East Anglia in the UK raised the objection that seaweeds release halogen-containing gases that could interfere with atmospheric chemistry. Read more: https://www.newscientist.com/article/mg24632821-100-kelp-is-coming-how-seaweed-could-prevent-catastrophic-climate-change/#ixzz6vnDUZoRV

The costs of dredging and trawling

24. Enric Sala, Juan Mayorga, Jane Lubchenco, (2021) *Protecting the global ocean for biodiversity, food and climate,* Nature 17 March 2021

Abstract

The ocean contains unique biodiversity, provides valuable food resources and is a major sink for anthropogenic carbon. Marine protected areas (MPAs) are an effective tool for restoring ocean biodiversity and ecosystem services, but at present only 2.7% of the ocean is highly protected. This low level of ocean protection is due largely to conflicts with fisheries and other extractive uses. To address this issue, here we developed a conservation planning framework to prioritise highly protected MPAs in places that would result in multiple benefits today and in the future. We find that a substantial increase in ocean protection could have triple benefits, by protecting biodiversity, boosting the yield of fisheries and securing marine carbon stocks that are at risk from human activities. Our results show that most coastal nations contain priority areas that can contribute substantially to achieving these three objectives of biodiversity protection, food provision and carbon storage. A globally coordinated effort could be nearly twice as efficient as uncoordinated, national-level conservation planning. Our flexible prioritisation framework could help to inform both national marine spatial plans and global targets for marine conservation, food security and climate action.

Carbon stored in marine sediments and the damage done by bottom trawling

Marine sediments are the largest pool of organic carbon on the planet and a crucial reservoir for long-term storage 29. If left undisturbed, organic carbon stored in marine sediments can remain there for millennia 30. However, disturbance of these carbon stores can remineralise sedimentary carbon to CO_2, which is likely to increase ocean acidification, reduce the buffering capacity of the ocean and potentially add to the build-up of atmospheric CO_2. Thus, protecting the carbon-rich seabed is a potentially important nature-based solution to climate change 11,31. Using satellite-inferred information on fishing activity by industrial trawlers and dredgers between 2016 and 2019, aggregated at a resolution of 1 km^2, we estimate that 4.9 million km2 or 1.3% of the global ocean is trawled each year. This disturbance to the seafloor results in an estimated 1.47 Pg of aqueous CO_2 emissions, owing to increased carbon metabolism in the sediment in the first year after trawling. If trawling continues in subsequent years, emissions decline as sediment carbon stocks become exhausted. However, after 9 years of continuous trawling, emissions stabilise at around 40% of the first year's emissions, or around 0.58 Pg CO_2 (Supplementary Fig. 35). If the intensity and footprint of trawling remains constant, we estimate that sediment carbon emissions will continue at approximately 0.58 Pg CO_2 for up to around 400 years of trawling, after which all of the sediments in the top metre are depleted. Although 1.47 Pg CO_2 represents only 0.02% of total marine sedimentary carbon, it is equivalent to 15–20% of the atmospheric CO_2 absorbed by the ocean each year 32,33, and is comparable to estimates of carbon loss in terrestrial soils caused by farming 34. Although an unknown fraction of the aqueous CO_2 is emitted to the atmosphere, the increase in CO_2 in the water column and sediment pore waters can have far-reaching and complex effects on marine carbon cycling, primary productivity and biodiversity 29,35. We identify areas where MPAs can effectively prevent the remineralisation of sediment carbon to CO_2 that results from anthropogenic disturbances 36. Top priority areas are located where carbon stocks and present anthropogenic threats are highest, including China's EEZ, Europe's Atlantic coastal areas, and productive upwelling areas (Fig. 1e). Countries with the highest potential to contribute to the mitigation of climate change through protection of carbon stocks are those with large EEZs and large industrial bottom trawl fisheries. The global benefit of protection for sediment carbon accrues sharply, because the spatial footprint of bottom trawling is small. At our working resolution of 50km × 50 km, eliminating 90% of the present risk of carbon disturbance due to bottom trawling would require protecting 3.6% of the ocean (mostly within EEZs) (Fig.1f). Deep-sea mining is another emerging threat to sediment carbon, but its spatial footprint is so far unknown as this industry is only now developing.

25. Callum Roberts, (2013) *Ocean of Life*, Penguin

This book details the damage done to marine ecosystems by several hundred years of unmanaged overexploitation. The following paper illustrates the connections between the terrestrial and marine ecosystems

26. James M. Helfield; Robert J. Naiman. (2001) *Effects of Salmon-Derived Nitrogen on Riparian Forest Growth and Implications for Stream Productivity*. Ecology, vol 82, Issue 9, pp. 2403-2409

The following is not about seaweed but I have added it for those interested in the co-evolution of the living and non living earth

It may be that it takes a living world to maintain plate tectonics over geological time. And that plate tectonics is necessary to maintain the supply of nutrients on which life depends. Because without the constant release of elements like phosphate from continental rock life would eventually run out of the chemicals it needs. Thus life creates a feedback loop with geology that creates the conditions needed by life to exist for a long time. Tilman Spohn and Dennis Höning in Berlin used a computer simulation to explores what would have happened on earth with and without life. [9] In the living world simulation algae and bacteria increase erosion of the land and more sediment is dumped into the ocean. The wet sediment is eventually subducted by tectonic plates and melts at depth. The wet molten rock is buoyant so it rises and erupts as lava from volcanos building continental plate. The simulation settles into equilibrium with a world that is about forty per cent land. In the dead world simulation, there is less erosion, the subducted mantle is drier, the continental crust is renewed more slowly and the model settles toward a world of ocean and island arcs. (But be aware the discussion about this is not settled. Robert Hazen in the USA argues chemical weathering of rock by acid rain in a dead CO_2 rich atmosphere would also create the sediment needed to drive plate tectonics and hence to maintain large landmasses.)

27. Höning, D., H. Hansen-Goos, A. Airo and T. Spohn. *Biotic vs. abiotic Earth: A model for mantle hydration and continental coverage*. Planetary Space Science, special issue 'Planetary evolution and life', doi:10.1016/j.pss.2013.10.004

There are many other such threads to follow.

A note about the work that is hidden within this talk.

I have always read and studied widely. How else is it possible to begin to begin to understand the earth system? I have studied naval architecture and aeronautical engineering, ecology, oceanography, and meteorology. In relationship to this place, that study has included transcribing several 19th and early 20th century textbooks and digitising historical statistics, partly as a meditation, partly to get text and data in a form that is easy to search and to plot, and partly because the only way to understand the changes that have taken place over the last two hundred years is to read and work slowly taking time to allow understanding to settle in. To give a few concrete examples I transcribed a PhD. Thesis about the social structure of the highlands, (including a chapter on Coigach), during the years before and after 1745, a book about the history of herring fishing, and the Scottish sea fisheries statistical tables. And during the first lockdown, I transcribed Alfred Kroeber's Indian's of California (published in 1927) because I am interested in the cultures of the peoples who inhabited the Americas before Europeans overran their world.

A. L. Kroeber, *Handbook of the Indians of California*, Smithsonian Institution Bureau Of American Ethnology Bulletin 78, Washington Government Printing Office 1925 (I can provide this book as edited, formatted, plain text.)

The Yurok used seaweed for salt, p84, "Salt was furnished by a seaweed, *Porphyra perforata*." (A red seaweed) and traded it with other tribes, as did many other tribes. e.g. The Costanoans p467

Picture credits

Diversity of coccolithophores
Emiliania huxleyi, the reference species for coccolithophore studies, is contrasted with a range of other species spanning the biodiversity of modern coccolithophores. All images are scanning electron micrographs of cells collected by seawater filtration from the open ocean. (A to N) Species illustrated: (A) Coccolithus pelagicus, (B) Calcidiscus leptoporus, (C) Braarudosphaera bigelowii, (D) Gephyrocapsa oceanica, (E) E. huxleyi, (F) Discosphaera tubifera, (G)

Rhabdosphaera clavigera, (H) Calciosolenia murrayi, (I) Umbellosphaera irregularis, (J) Gladiolithus flabellatus, (K and L) Florisphaera profunda, (M) Syracosphaera pulchra, and (N) Helicosphaera carteri. Scale bar, 5 µm.

Date 13 July 2016

Source https://advances.sciencemag.org/content/2/7/e1501822

Author Monteiro, F.M., Bach, L.T., Brownlee, C., Bown, P., Rickaby, R.E., Poulton, A.J., Tyrrell, T., Beaufort, L., Dutkiewicz, S., Gibbs, S. and Gutowska, M.A.

https://commons.wikimedia.org/wiki/File:Diversity_of_coccolithophores.jpg

Chalk cliffs

Old Harry Rocks are three chalk formations, including a stack and a stump, located at Handfast Point, on the Isle of Purbeck in Dorset, southern England. They mark the most eastern point of the Jurassic Coast, a UNESCO World Heritage Site

https://tinemaria.com/white-cliffs-of-dover-2/

Carbon stocks visualised

Diagram showing relative sizes (in gigatonnes) of the main storage pools of carbon on Earth. Cumulative changes (thru year 2014) from land use and emissions of fossil carbon are included for comparison.

From: Kayler, Z., Janowiak, M., Swanston, C. (2017). *"The Global Carbon Cycle"*. *Considering Forest and Grassland Carbon in Land Management*. General Technical Report WTO-GTR-95. United States Department of Agriculture, Forest Service. pp. 3–9.

Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2010–2019.

See legends for the corresponding arrows and units. The uncertainty in the atmospheric CO_2 growth rate is very small (±0.02 GtC yr^{-1}) and is neglected for the figure. The anthropogenic perturbation occurs on top of an active carbon cycle, with fluxes and stocks represented in the background and taken from Ciais et al. (2013) for all numbers, with the ocean gross fluxes updated to 90 GtC yr^{-1} to account for the increase in atmospheric CO_2 since publication, and except for the carbon stocks in coasts which is from a literature review of coastal marine sediments (Price and Warren, 2016). Cement carbonation sink of 0.2 GtC yr^{-1} is included in EFOS.

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The global carbon cycle for the 1990s

IPCC Fourth Assessment Report: Climate Change 2007