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WORLD SCIENTISTS' WARNINGS INTO ACTION, LOCAL TO GLOBAL

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Abstract

"We have kicked the can down the road once again - but we are running out of road." - Rachel Kyte, Dean of Fletcher School at Tufts University

We, in our capacities as scientists, economists, governance and policy specialists, are shifting from warnings to guidance for action before there is no more 'road.' The science is clear and irrefutable; humanity is in advanced ecological overshoot. Our overexploitation of resources exceeds ecosystems' capacity to provide them or to absorb our waste. Society has failed to meet clearly stated goals of the UN Framework Convention on Climate Change. Civilization faces an epochal crossroads, but with potentially much better, wiser outcomes if we act now.

*What are the concrete and transformative actions by which we can turn away from the abyss? In this paper we forcefully recommend priority actions and resource allocation to avert the worst of the **climate and nature emergencies,** two of the most pressing symptoms of overshoot, and lead society into a future of greater wellbeing and wisdom. Humanity has begun the social, economic, political and technological initiatives needed for this transformation. Now, massive upscaling and acceleration of these actions and collaborations are essential before irreversible tipping points are crossed in the coming decade. We still can overcome significant societal, political and economic barriers of our own making.*[1]

Previously,[2-4] *we identified six core areas for urgent global action – energy, pollutants, nature, food systems, population stabilization and economic goals. Here we identify an indicative, systemic and time-limited framework for priority actions for policy, planning and management at multiple scales from household to global. We broadly follow the 'Reduce-Remove-Repair' approach*[5] *to rapid action. To guide decision makers, planners, managers, and budgeters, we cite some of the many experiments, mechanisms and resources in order to facilitate rapid global adoption of effective solutions.*

Our biggest challenges are not technical, but social, economic, political and behavioral. To have hope of success, we must accelerate collaborative actions across scales, in different cultures and governance systems, while maintaining adequate social, economic and political stability. Effective and timely actions are still achievable on many, though not all fronts. Such change will mean the difference for billions of children and adults, hundreds of thousands of species, health of many ecosystems, and will determine our common future.[6]

I INTRODUCTION

Most people can now see that our planet is literally and metaphorically burning: massive wildfires; record temperatures; sustained, life-threatening high heat events and droughts; record floods; intensified tropical storms; species under high threat. We have already crossed tipping points like sea level rise and Arctic sea ice loss that will take a millennium (40 generations) or more to restore.[1] Climate change is the best known, but by no means only symptom of exceeding planetary boundaries.[7]

The World Scientists' Warning of a Climate Emergency paper[2] - endorsed by a total of 14,236 scientists from 158 countries by October 2021 - identified six priority areas for global action. Two updates[3,4] found that few successful actions had been taken and that climate indicators had worsened, despite the COVID-19 pandemic.

What values and systems led humanity to this point, and where do we go from here?

The frequency of massive droughts, heatwaves, wildfires, and intensified storms and floods has begun to convince society and its leaders that immediate action is essential. Carbon and heat trapped in our oceans and atmosphere already guarantees that we will exceed 1.5C.[8] High temperatures and sea levels will likely persist for millennia or longer.[9] We can mitigate the severity of weather events to some extent if we employ significant climate restoration methods before 2030. Not only should global society redouble its decarbonization commitments, it should also take thoughtful, equitable and decisive action, both to help citizens adapt to a less energy-intensive future and to develop workable methods to extract carbon and methane from our atmosphere and oceans at an aggressive rate.

Having wasted precious decades, we now face severe timelines to accelerate the societal, political and economic implementation of climate solutions, as scientists have called for publicly for decades.[10-13] The faster we can invest in the future, the less it will cost. Complex natural systems under stress, like the climate, do not change gradually or predictably. Critical thresholds (tipping points) may be unknown before they are breached and, once breached, the consequences may be irreversible. Many climate scientists fear that the 1.5 or 2.0 C degree Paris Accord targets, while ambitious in the current political context, are insufficient and could push us irreversibly onto a 'Hothouse Earth' pathway.[14]

Climate restoration, not just mitigation and adaptation

Ensuring humanity's long-term survival requires climate repair by reducing greenhouse gases (GHG), including methane, to earlier levels that we and other species have survived in the long-term. Earth's rising CO_2 levels are now higher[10] than at any time in at least the past 800,000 years[15] and 48% higher than pre-industrial levels. Nature has previously regulated GHG to maintain a habitable climate,[10] and it is essential that we try to restore those conditions.

By collaborating and acting rapidly, we can indeed slow changes by 2030 and 2050, and start to reverse them during the rest of the century.[1] To make this happen, we should transform our global economy by 2030 to at least halve emissions of CO_2 and other GHG, and to increase removals from the atmosphere of methane, tropospheric ozone, carbon soot and hydrofluorocarbons by natural systems and other means. This is absolutely necessary to achieve significantly negative emissions by 2050.

At the same time, we can rapidly learn to use resources much more efficiently, to require less of them, and to develop and adopt alternative technologies.

Stringent protection and restoration of natural systems are critical to success

Global heating can eventually be reversed, after the drawdown of atmospheric CO_2 and methane by natural and anthropogenic systems starts to exceed annual additions from all anthropogenic and natural sources. To reach and exceed net-zero carbon, we would need to immediately halt the destruction and degradation of critical carbon-accumulating ecosystems like forests, wetlands and grasslands. The two global bodies, the Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), jointly concluded that to succeed, climate change and biodiversity loss must be addressed rapidly and together.[16]

Designing a global 'Marshall Plan' for civilization

So what actions are needed by 2026, 2030 and 2050 to turn this grim situation around? Here we identify an indicative, systemic array of priorities for policy, planning and management at multiple scales, individual to global (see also[17]). Implementing these will require rethinking the constraints and values that habitually frame planning, resourcing and decision making.

"If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted"[18], a global Marshall Plan-style transformative collaboration can and should legally end destructive actions taken for short-term self- and national- interests. We can build an economy which embraces values and policy goals capable of restoring our wounded planet, its people and biosphere.

II MOVING FROM CLIMATE WARNINGS TO CLIMATE ACTIONS

The **six urgent areas** identified for action in the World Scientists' Warning of a Climate Emergency[2] and its updates[3,4] are: energy, atmospheric pollutants, nature, food, population and economy.

This paper aims to support decision makers at different scales - household, community, city, district/state/province, nation, global - in planning and implementing the urgent actions on energy, pollutants, nature, food systems, population and the economy by 2026, 2030 and 2050. Our approach cannot be both global and comprehensive, but we suggest actions to support the prioritization, scheduling, budgeting and identification of unmet needs at different scales and in different regions. We also identify those areas currently most amenable to individual, household and community actions in many countries. As a cross-cutting action, we also identify (section III) some of the very basic procedures of government and other large organizations which still block progress. It is essential that actions be well underway in the five-year period 2022-2026.

Actions will likely fail if planned in isolation from deep systemic change, or from collaboratively agreed alternative visions. We do not articulate our own visions, as these must be the products of action by participants at all scales. Yet as a global society at a crossroads of the most critical kind, we should all ask the questions faced by societies at transformative moments: "What kind of a society do we want to have now? And how do we get there from here?"

Humanity has both a daunting challenge and a vast opportunity. By reforming past destructive practices, societies globally can achieve multiple deep and lasting benefits - for human and planetary health, biodiversity, water and air quality, food security, mental and physical wellbeing, human relationships and community cohesion. If successful, we will look back from a safe place and wonder what took us so long to overcome destructive trends and antagonists in our society.

1. ENERGY

Civilization requires energy for industry, heat, electricity, transportation, construction, agriculture - indeed, all human activities. Today, fossil fuels (FF) are the major source of primary energy for these services and the productivity or conversion efficiency is extremely low. To meet sufficient emissions reductions requires integrated efforts to greatly reduce energy requirements and replace primary energy with zero-carbon renewables.

Reducing demand, increasing decarbonization, efficiency and innovation

Conservation and improved productivity of energy are essential counterparts to innovation and low-carbon generation. At all scales from households to nations, these should and can be massively accelerated: e.g. better thermal building insulation in hot and cold climates, redesigning cities for walkability and cyclability, local and home-based work, transition to LED lighting for just one-fifth of the electricity use. Heat pumps provide the same space heating at one-fourth to one-third the electricity, and high performance buildings need as little as 20% of the energy[19] required by standard structures. Electric cars require just 20% the energy of same-sized petrol vehicles. The rate of change in energy productivity must exceed the growth in energy demand globally. Additional energy will be required for remediation to clean and restore ecosystems, including clearing ocean plastic garbage, remediating water and soils damaged by toxic chemicals, restoring and rewilding post-industrial landscapes and remediating ocean dead zones. However, these new uses can power the new restoration economy.[20]

By imposing carbon pricing and focusing heavy taxes[21] on “luxury” travel and trade, especially flights, inefficient vehicles and imported luxury goods, carbon emissions will be significantly reduced in a decade.[22] To achieve these goals requires an immediate energy transformation roadmap far more assertive and far less platitudinal than the actions being discussed today.

Relocalizing, regeneration, redesigning, retrofitting, and resilience

Over the next decade, towns and cities in many countries will be increasingly reconfigured to facilitate walking, cycling, and green electric public transport, around community hubs improving equitable access and social justice (accommodation, work and leisure activities integrated within the same area). Retrofitting buildings, decentralised energy generation, low energy local food growing and soil improvement are all essential, cost-effective investments in community resilience and energy efficiency.[23] Restoring/rewilding and protecting natural habitats[24] within and around human communities enables low-maintenance pollinator corridors and habitat, thus turning cities, towns and villages into a network of insect reserves.

To address the most pressing challenges of society, we need to move beyond sustainability towards regeneration.[25] This means that spatial planning and zoning would increasingly embrace complexity and interconnectivity, rather than the car-centered linear isolation and siloed planning of the past industrial era. Encouraging repair cafes and makerspaces,[26] as exist less formally in many developing countries, would reduce plastic and overall waste, resource consumption, and greenhouse/landfill emissions.

Some necessary steps toward these objectives might include (adapted from Rees[27]):

- Manage regional economies and commerce to sustain the population as much as possible on regional resources to reduce reliance on carbon-intensive trade goods.
- Relocalize light manufacturing, food production and processing as much as possible to enhance regional self-reliance, increase economic diversity and employment security, and bolster community pride and cohesion.
- Re-engineer urban utilities to convert cities and towns from resource-depleting linear throughput systems into self-sustaining circular-material flow systems, e.g., convert waste streams into resources; collect, treat and recycle animal and domestic wastes on local farmlands, thus restoring soil quality, reducing the need for artificial fertilizers, and eliminating ground and surface water pollution.
- Actively promote agroecological and permacultural practices to improve quality food production, reduce FF-intensive fertilizer and pesticide use, and provide extension and training programs for farmers in ecologically and socially restorative production methods.
- End essentially all conversion of arable land. Invest program money in long-term restoration of depleted soils, degraded landscapes, forests, wetlands and grasslands to promote biodiversity, enhance regional productivity, increase carbon accumulation, and mitigate climate change. Humans have destroyed half the world's forests, wetlands and topsoil, but soil still contains[28] several times as much carbon as the atmosphere.
- At city and community scale, build up rather than out. Densify existing transformed areas in ways that spatially reintegrate work-places with living and recreation areas.
- Use economies of scale that confer a substantial 'sustainability multiplier' on well-designed high-density settlements: e.g., reduced per capita demand for space and transport, low-cost or free public transit, higher potential for recycling, reuse and remanufacturing, and district heating/cooling; expanded opportunities for co-housing, tool-sharing and other activities that reduce material demand.

This is an opportunity for humanity and our resilience

Social and technical innovation presents major opportunities for greater productivity, improved balancing of human and ecological needs, and improved quality of life. The practical, cultural and logistic challenges of energy transitions from the status quo are complex,[29] but not more so than other ambitious human endeavors. In several decades they are quite possible - and of course essential for the survival of civilization and a stable, habitable planet. Reduction in energy consumption, especially among those who consume the most, is inevitable[30] and even desirable, given innovations that support greater wellbeing on lighter footprints.

Finally, even at peak wind and solar electricity production, less energy will likely be available to humankind in the future than now. A carefully designed decrease in global energy demand is necessary for this reason. Relocalisation would significantly curb energy demand,[31,32] mitigate

GHG emissions, build community resilience,[32] improve health and wellbeing, increase energy security, and reduce supply chain vulnerability.[33]

2. ATMOSPHERIC POLLUTANTS

Our current accumulation of atmospheric carbon, its acidification of our oceans, and the dangerous increases of methane, nitrous oxide, hydrofluorocarbons and air pollutants in our atmosphere, have far exceeded even the worst case scenarios projected by the scientific community decades ago. Methane (CH_4) is the second largest contributor to global heating after carbon dioxide (CO_2), almost 90 times more potent than CO_2 over 20 years[34], but it has a relatively short average lifetime in the atmosphere of 12 years. Current methane levels are at 800,000-year highs and rising rapidly. Since 2007 there has been a particularly sharp rise in atmospheric methane[35] that is not well understood, with 2020 posting the largest annual growth on record. According to the 2021 IPCC WG1 report,[1] methane has already caused one-third of global heating, and has contributed at least half as much warming as CO_2.[1]

The possible pathway assessed in the AR6 IPCC[1] report to keep global heating below 1.5C assumes enormous reductions of methane emissions by 2050. The largest source of anthropogenic methane emissions globally is agriculture - especially livestock for meat and dairy products. These emissions can be reduced, but are impossible to eliminate completely. About 40% of global methane emissions are from natural sources such as wetlands,[36] which could increase as global temperatures rise. Degrading or destroying wetlands rapidly releases additional methane and CO_2, so protecting them is an essential, effective strategy. The Arctic is warming dramatically, with potentially catastrophic climate impacts through rapid mobilization of giant reservoirs of carbon sequestered in permafrost. Thawing permafrost and collapsing methane hydrates in the Arctic may move substantial amounts of carbon from land and ocean to atmosphere (as CO_2 and CH_4) on decadal-century timescales. Destabilization of shelf Arctic hydrates could lead to large-scale increases of aqueous and atmospheric CH_4.[37] Thawing permafrost on land can only be controlled by reducing temperatures in the Arctic. In addition to aggressively mitigating methane emissions wherever we can, we should reduce other GHG emissions to compensate for natural and anthropogenic methane emissions that we cannot effectively reduce or eliminate. Yet the potential massive release of CH_4 from the subsea permafrost cannot be mitigated. An overarching goal is to transform this area from a data-lean and largely descriptive state to provide breakthrough understanding of one of the largest challenges today: the vulnerability of the Arctic's giant seabed carbon/hydrate pool to progressive subsea permafrost degradation.

Reduce, remove, repair - and monitor

In order to take effective action on the methane crisis, all jurisdictions can aggressively reduce or mitigate emissions of methane at their sources wherever possible - agricultural, industrial, oil and gas production. One such approach is to require all new household appliances and buildings to be electric in areas where renewable energy makes up a large and rapidly increasing part of the electric supply, as several jurisdictions have done.[38] Another approach is to shift subsidies for large methane-producing meat and dairy firms and FF companies to fees on large methane producers. At household, community and corporate levels, except perhaps in dry rangeland nations, eating less meat and dairy from current production methods can reduce direct methane emissions and altered grazing practices can actually increase soil carbon accumulation.[39]

In addition, local, state and federal authorities can assess, prioritize and require the use of best available technologies for reduction and removal of methane emissions, while also supporting policies, practices and technologies for the development of atmospheric methane removal at national and international levels.

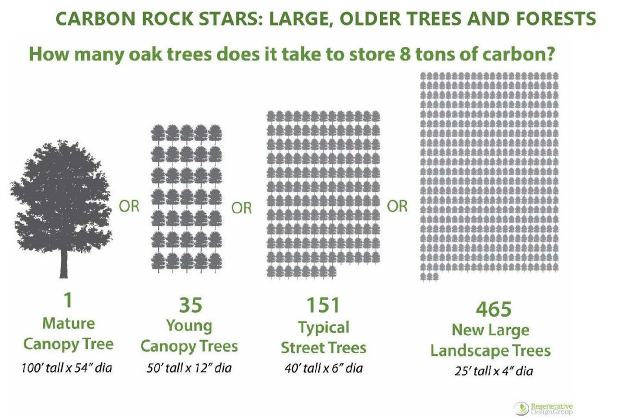
Simultaneously, the global community should initiate programs to monitor atmospheric methane reductions, fund and initiate programs to develop technologies and natural practices (e.g. methane-loving bacteria) that reduce atmospheric methane safely and effectively, provide funding for documented atmospheric methane level reduction, and frame and implement global governance requiring the use of such methods to return atmospheric methane to preindustrial levels as rapidly as possible.

Nitrous oxide is the third largest direct contributor to global heating and now the largest depleter of stratospheric ozone. It arises from bacterial metabolism of excessive nitrogen fertilizer, FF combustion and industrial processes. The most effective way to control agricultural emissions is to use less fertilizer by better timing smaller amounts during the annual growth cycle.

Other nitrogen oxides associated with combustion produce tropospheric ozone, which has contributed more to global heating than nitrous oxide. Fortunately, tropospheric ozone is relatively short-lived in the atmosphere. Nitrogen fertilizers added to biofuel crops are problematic in this context, but if FF combustion vehicles are replaced by electric or fuel cell technologies where electricity and hydrogen come from zero-emitting sources, the effect of heating by tropospheric ozone would rapidly disappear, and no nitrous oxide from fertilized biodiesel or bioethanol vehicle crops would be burned into the atmosphere.

3. NATURE

Our current crises of climate change, biodiversity loss and cultural disenfranchisement are all rooted in the widespread degradation, destruction and commodification of land and natural resources. Few ecosystems or ecoregions are sustainably managed for biodiversity and carbon as well as production, and few have escaped adverse alteration through extractive economies and methods. This has crippled complex, interdependent ecosystem processes - like pollination, natural flood control and water purification.[40] In many regions, the ecosystem goods and services provided to humanity and other species are no longer available. The consequences of lost ecosystem services are profound. While humans constitute just 0.01% of total living biomass, the expansion of the human enterprise has eliminated 83% of wild animals and 50% of natural plant biomass. From a fraction of 1% ten millennia ago, humans now constitute 36%, and our domestic livestock another 60%, of the planet's much expanded mammalian biomass - compared to only 4% for all wild mammals combined.[41,42]



"A large northern red oak measures 14 feet in circumference [54 inches diameter at breast height (dbh)]. Its height is 100 feet. Approximately 50% of this dry weight is carbon, or 7.7 tons. This amount of carbon has a CO_2 equivalency of 28.2 tons. Let's say we have a 12-inch dbh, 50-foot tall, young northern red oak. It would take 35 young trees to match the carbon of the one large oak. Using a 6-inch dbh, 40-feet tall oak, the number of young trees needed to match the one big tree soars to 151! Finally, let's drop to a 4-inch DBH and 25-foot height. The number of oaks required skyrockets to 465! It takes 10 or more years to get a young red oak up to this [4-inch dbh] size...Let's take a young, newly planted tree from nursery stock…its diameter is 1 inch and it is 4.5 feet tall…it would take 61,364 newly planted trees to match the carbon in our one large oak, and they would be three years old!...Assuming each 1-inch diameter seedling controls only 5 ft^2 of ground space, then the total area needed to hold the seedlings becomes…7.0 acres… The lesson is clear: Save big trees where possible." - Robert Leverett, Cofounder, Native Tree Society

Source: Leverett R.T. 2021. Carbon Storage in Large vs Small Trees – an Example. Unpublished Text.
Also See: Leverett R.T., Masino S.A, and Moomaw W.R. 2021. Older eastern white pine trees and stands accumulate carbon for many decades and maximize cumulative carbon. Frontiers in Forests and Global Change 4: 620450. doi: 10.3389/ffgc.2021.620450

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Fig. 1. A US example of collaborative municipal natural climate solutions emphasizing the value of saving mature trees in carbon terms. Credits as above.

Nature is all-encompassing in its benefits - not just a set of commodities

Protecting oceans, natural landscapes, and remaining primary forests[43] are critical for successfully accumulating carbon out of the atmosphere. Afforestation, from planting trees, has relatively little impact on increasing forest carbon. But trees alone do not make a forest. Proforestation is the practice of purposefully growing existing forests intact toward their full ecological potential, as a nature-based solution protecting existing intact ecosystems to maximize carbon storage, biodiversity, and structural complexity, including soil, mycorrhizal fungi, insects, plants, lichens, etc.[44,45] while avoiding emissions from harvesting of forest products.[46] Existing forests and grasslands could likely store twice as much carbon as they currently do under alternative management practices.[47] A study on western U.S. forests found that reducing harvest by half of public lands would accumulate 10 times the carbon by 2100 as planting trees now.[48]

If we exceed the global goal of protecting an *effective* 30% of land and water by 2030,[49] while rapidly halving FF use, natural systems can likely accumulate and store sufficient atmospheric carbon and biodiversity to restore safety and stability to our climate and ecosystems. For the past 60 years, natural ecosystems have removed 56% of all atmospheric CO_2 added to the atmosphere by human actions: 31% by existing forests and land plants, and 25% by oceans.[1] It is essential to accelerate this removal of atmospheric CO_2 by protecting and restoring forests and other land ecosystems, coastal mangroves and marshes, and ocean kelp forests.[50,51] Yet a disturbing number of tropical[52] and temperate forests (Brazil and Canada) are now increasingly susceptible to fragmentation, wildfires and invasive pests, and no longer store more carbon than they release to the atmosphere.[53] They have become carbon sources, instead of sinks.[54]

Conservation, restoration, rewilding will get our civilization back on track

Widespread conservation, restoration and rewilding are needed to help natural habitats recover sufficient resilience to support the survival and migration of biodiversity, including humanity, in the face of now-inevitable climate disruption. This is why bold goals such as the UN Decade of Ecosystem Restoration, setting aside 30% of land and water by 2030 to protect biodiversity through the Convention on Biological Diversity, and IUCN Motion 101, calling for setting aside 50% of our planet for nature, are essential - even if perceived as unattainable within current economic and political systems. But such a goal requires a roadmap of action at local, regional, national, and global levels. These actions must begin showing real headway in implementation within the 2030 decade to be effective at securing our life-support system.

For the next decade we strongly recommend concerted actions in three areas associated with Reduction, Removal and Repair (restore), at all scales from household to global:

(a) Actions to reduce (2022-2026) and then halt (2027-2030) habitat transformation, even in peri-urban areas, through policies and bylaws for densification, sprawl reduction, rezoning and repurposing and multi-purposing of underused transformed habitats (e.g. extensive lawns, strip malls, and associated parking areas);

(b) Actions to remove pollutants from habitats, especially wetlands, soils and air, e.g. through remediation of pesticides from soils, removal of lead shot from wetlands; removal of airborne toxins through point-source interventions; an important action would be the gradual internalization of all externalized costs (e.g. pollution), reduce unnecessary consumption and conserve resources;

(c) Actions to repair (restore) prioritized critical habitats, including the rewilding of ecosystems which have been depleted, particularly of apex predators and economically important species and groups that shape and stabilize food webs;

(d) Actions to restore natural systems should include all plants, macro animals, insects, fungi, lichens, soil and other bacteria and viruses that are components of a functioning ecosystem and exclusion of invasive species to the extent possible.

(e) Actions to halt the burning of 'forest bioenergy' wood as a replacement for FFs, and the subsidies that support the practice. This is more carbon intensive than burning coal, and reduces the accumulation capacity of the forest because of the loss of the harvested trees and associated disturbance.

Bioenergy continues to be subsidized in Europe, North America, Japan and elsewhere, despite the carbon burden, air pollution, environmental justice issues, and very high cost.

Oceans annually remove and prevent an additional 25% of atmospheric CO_2 increase[1] and store vast amounts of dissolved CO_2 in several chemical forms, but this has led to long-term acidification of the oceans, threatening coral reefs and many other living organisms and imperiling ocean food webs and global food security.[55] As ocean temperatures rise and society diminishes its emissions of CO_2, oceans will release some carbon back to the atmosphere, slowing climate recovery.[1]

To "stabilize greenhouse gases in the atmosphere at a concentration that will avoid dangerous anthropogenic interference with the climate system"[56] requires rapidly reducing CO_2 and other greenhouse gas emissions, while simultaneously increasing accumulation of carbon in forests and other natural systems to remove as much atmospheric CO_2 as possible. Photosynthesis by forests and other land and ocean plants is the major means for removal. Proposed technological CO_2 removal is receiving attention and may be useful in limited circumstances, but the scale of construction and energy intensity of removal and storage suggests this may have limited utility. A useful quantitative summary of natural CO_2 removals is in the Drawdown Table of Solutions.[57] Major natural solution benefits are estimated for forest protection, restoration of temperate and tropical forests, restoration of abandoned farmland soils, and peatland protection and rewetting.

Cities and communities have big roles to play

While major mandates for these actions sit at national, state/provincial, and county/district levels, the most rapid and visible progress is often at more local city and community levels. Local intensification to serve people in urban centers can leave more of the surrounding land available for nature and natural processes. Within urban areas, urban trees provide shade and evaporative cooling. Multipurpose urban food and energy gardens, densification and rezoning for climate adaptation, multipurpose urban hubs, and restoration of landfills and industrial lands for urban parks all use natural processes to provide needed services. Orlando, Florida, USA is a good example of municipal reimagining of cities for biodiversity, people and carbon benefit.

4. FOOD SYSTEMS

After decades of improving nutrition levels, since 2014 the number of undernourished people in the world is once again increasing.[58] Extended and more frequent weather extremes such as droughts, are impacting and will increasingly impact food production at local and global scales. A few regions, mainly in northern latitudes, may see increased crop yields, but those in the tropics and semi-arid zones are more likely to suffer net negative effects.[59]

Limits to production are already being reached

Although food production is projected to increase by up to 70%[60] by 2050, its current impacts are already vastly beyond levels that comply with planetary health goals. The food system is responsible for more than a quarter of GHG emissions,[61] around 70% of freshwater use, most deforestation and nutrient run-off leading to freshwater and coastal dead zones.[62] Nearly doubling food production would increase GHG emissions proportionately if current patterns of production and consumption persist.[63] Even if FF emissions were halted immediately, ongoing emissions from the food system would make limiting global temperature rise to 1.5°C unattainable.[64] Fresh water is already being used in unsustainable volumes, with major aquifers depleting[65,66] and many of the world's great rivers barely reaching their deltas for much of the year due to over-extraction, causing seawater to invade the valuable delta soils.[67] Soils are being degraded due to overuse, or lost under urban development and infrastructure. And an increasing proportion of fisheries are also in a parlous state of over-exploitation.[58] Fertilizers such as phosphorus and potassium could become scarce and costly as more accessible sources are mined out.[68] Production of nitrogen fertilizers can shift from dependence on natural gas to electrolytic processes,[69] and greatly increased nitrogen use efficiency will be necessary to minimise nitrogen pollution.[70]

If we continued business-as-usual food production to 2050, even optimistic yield improvements would be insufficient to prevent agricultural expansion to new areas, causing emissions from carbon sinks.[71-73] Globally, crop yields increased by 56% between 1965 and 1985, but only 20% between 1985 and 2005, despite substantial, and unrepeatable, increase in the area irrigated.[74] Major staple crops are reaching their genetic potential, barring major breakthroughs in genetic engineering which are not guaranteed.[75]

Aligning food systems with planetary health goals

By one estimate, current production and consumption patterns could sustainably provide a balanced diet for only 3.4 billion people.[76] Shifting supply and demand has the greatest potential to reduce food system impacts. Specifically, reducing meat and dairy demand and moving to plant-based dietary patterns provides the greatest benefits across the suite of environmental impacts from the food system - substantially reducing GHG emissions and the requirement for land, water, pesticides and fertilizers.[77,78, 63, 61,79] Water management is critical for increasing crop production to match demand. Currently 40% of irrigated crops use water resources at an unsustainable rate, causing aquifer depletion or inadequate environmental flows.[80] However, irrigation could be sustainably extended to around 26% of currently rainfed croplands, potentially increasing global calorie production by 37%[80] To achieve greater production growth, water and land use efficiency should be paramount.[81]

Increasing cropping intensity tends to degrade soil carbon if not expertly managed. An estimated 116 Gt of carbon (425 Gt CO_2) have been released from soils over the history of agriculture, most of it in the past 50 years.[82] Although increasing soil carbon has been widely promoted as a means of climate change mitigation, there are formidable social, technical and logistical challenges to reversing soil carbon loss even in developed countries, and the prospects for net gains on a global scale are severely undermined by the growth in food demand. Less reliable weather patterns are likely to increase soil damage from overgrazing in times of drought, and erosion during high rainfall. Often referred to as 'regenerative agriculture', soil protection practices need to be prioritized for food security, climate change mitigation and biodiversity.[25,83]

Taking a systems approach to food is essential

Relocalization of food supply has been advanced as a contribution to sustainability and food security. However, the length of supply chains is a poor indicator of environmental footprints.[84] Transport accounts for a relatively small portion (6%) of food system GHG emissions, with the majority resulting from production.[61]

Moreover, billions of people lack sufficient local production capacity to meet their food needs. In Africa and the Middle East, where almost all additional population growth is projected to occur, rapidly increasing dependence on imported staple foods combined with widespread poverty heightens vulnerability to supply shocks, such as those increasingly caused by extreme weather events.[85] Hungry people are angry people: a strong relationship exists between supply shocks, the global food price index and the incidence of violent unrest.[86] Low yields across Africa suggest potential for productivity gains to mitigate import dependence. Yet this will require large investments in infrastructure, especially for irrigation, and widespread uptake of fertilizers to overcome phosphorus deficiencies, stem acidification and replenish nutrients removed in crops.

Reducing food waste can substantially reduce demand for food.[87] Reducing harvest, storage and processing losses requires substantial investments in infrastructure, information systems and farmer training, so more attention is being given to consumer waste, stimulating many initiatives to reduce waste in domestic, retail and hospitality sectors.[88] There is some hope of achieving the Sustainable Development Goal of halving food waste by 2050.[88,89]

The range of actions required across the food system gives a potential role to stakeholders from local to global levels. National governments can facilitate production shifts through agricultural subsidies and incentives, including transitioning some farmers' livelihoods to new enterprises, which might extend beyond food production to the remit of habitat restoration to help meet climate and biodiversity targets. While production shifts are the most crucial element of food system transformation, it is also important to support consumers in aligning their diets with planetary health goals. Clear national dietary guidelines, in addition to supportive regional food systems are likely needed. City or institutional managers may adopt sustainable food procurement targets. For example, procurement targets in Oslo aim to halve meat consumption across the city's canteens and institutions by 2023, and halve food waste by 2030.[90]

In summary, action is needed across three major components of the food system: production, land, and farming practice.[91] Shifting production from high impact foods (such as animal products) to low impact foods (such as fruits, vegetables, legumes and grains), in addition to reducing food waste, is essential for reducing current environmental impacts and preventing further land conversion to agriculture. Even with such shifts, reducing the environmental impacts of farming is also required. This can be partly through the use of technology to increase efficiency of water use, for example, but also through adjusting farming practices to more regenerative and less environmentally degrading methods. Shifting production is the crucial enabling factor for food system transformation - allowing existing natural habitats to be protected (and carbon sinks maintained), and reducing agricultural land requirements in turn providing space for native vegetation (and carbon sinks) to be reinstated.

It is still conceivable that humanity can avoid major famines this century. But the convergence of so many resource limits and environmental crises demands urgent action across the entire global food system on many fronts simultaneously. Taking a systems approach is essential.

POPULATION STABILIZATION

Population growth and consumption are multipliers, exacerbating everything else

Global population is now roughly ten times the relatively stable pre-industrial level. The associated consumption demand is massively, disproportionately so. The 80+ million extra people added to the planet each year, equivalent to 10 New York Cities or a country the size of Germany, make solving the issues above all but impossible. Climate instability, ecological destruction, famine, social and political instability and insecurity, unprecedented suffering - all our good works to forestall these are undercut and overwhelmed simply by needing to cut the 'pie' into an additional 80+ million pieces each year.

Acknowledging population and consumption as the two fundamental 'multiplier threats,' in both public policy and broad public perception, globally and nationally, is the first step. The next is significantly increased human wellbeing investments, through ethical and empowering health, education and economic strategies assisting women and girls, and supporting men and boys. This can already start to bend the global population curve by 2030.[92] To significantly relieve our planetary and institutional resources by 2050, bold actions are required by 2026 at all scales.

Scenarios that avoid calamitous outcomes assume that global population growth will slow, and soon end. Yet this isn't happening globally: the 'demographic transition' that made such progress in the 1960s and 1970s slowed in the past 20 years, and investment in international family planning programs faltered over the past 25 years, despite continued population growth. Globally, births per woman fell by more than one in the 1970s, but by only 0.1 in the 2010s. With twice as many women of childbearing age as 50 years ago, births have never been more plentiful.[93] Much more deliberate action is needed. To stabilize population and ease global security, family planning should receive 4% of international aid budgets; women's and girls' voices should be heard on this, worldwide; and population and consumption should be integrated into economic, social and political agendas worldwide, at all scales.

Society is changing fast anyway, everywhere

Women are increasingly choosing smaller families, to ensure that their children are better provided for and to balance family life with economic and career opportunities. This is among the most effective steps to reduce one's impact on the planet.[94] Many young people also question the ethics of bringing children into a world so fraught with environmental crises.[95,96] For citizens of rich countries, having fewer children is the single most effective way to individually reduce future GHG emissions.[94,97] For those of poor countries, increasing economic and educational advancement and urbanization are rapidly changing birth rates, although increasing consumption.

Many countries have perversely tried to increase birth rates, through ill-founded fears of the economic impacts of an aging population. This ignores population growth's enormous contribution to countries' carbon and ecological footprints.[98] Such misconceptions contribute to chronic underfunding of reproductive health and family planning services, and growing numbers of women with unmet needs.[99] Fulfilling these unmet needs could avoid 21 million unintended births globally per year, while saving $3 on maternal and newborn health care for each dollar spent on contraceptive services.[100] The economic stimulus from slowing population growth repays the investment more than one hundredfold within a few years.[101]

Effective measures for bending the curve

Despite 25-years of shortfalls in intergovernmental support for family planning programs, some non-government initiatives have shown effective reach to under-serviced communities, and transcended cultural barriers to family planning acceptance. For example, Population Media Center's serialized radio and television dramas in local languages in 50+ countries expose people to new ideas and change attitudes toward women's roles, family violence and contraception.[102] Adequate global and national funding for these reproductive norm-shifting programs is an essential investment in human and planetary wellbeing.

A second positive development is the proliferation of Population-Health-Environment (PHE) projects. Few environmental or livelihood programs in the past addressed linkages between population growth and environmental stress, but this is changing. PHE projects integrate community health and family planning alongside resource management and livelihoods, often with greater community engagement and enthusiasm than single-sector projects.[103-105] Linking environmental health with population pressure improves men's support for family planning.[106] Yet such projects often lack sufficient scale and continuity of support. Improving these measures would enable a steady annual reduction of the pressure on our planet and climate.

While lowered GHG emissions may not motivate everyone to have smaller families, the improvement of family and community wellbeing certainly may. A smaller family improves women's health, infant nutrition, and access to schooling and employment prospects, while easing pressure on the environment. All contribute to greater resilience to climate change[107,108] and to achieving the Sustainable Development Goals.[109] After a few decades, the lower population trajectory becomes a dominant determinant of sustainable wellbeing.

Like planting a forest, our slow start only increases the urgency of our predicament. How we normalize lower birth rates in this decade will make the difference between having 12 billion or 7 billion people to sustain in 2100.[110] While accelerating the decline in fertility won't contribute much to phasing out FFs by 2050, it will significantly affect our trajectory for ending and reversing deforestation.[111-113,76] This is vital for achieving net-zero emissions.[115] An Earth in overshoot cannot sustain even the current 7.9 bn without unacceptable tradeoffs. We need to acknowledge this, and find ethical, equitable ways to support smaller families and rapidly bend the population and resource consumption curves.

5. ECONOMIC REFORMS

The global market economy represents a degree of social cooperation and coordination unprecedented in the history of *Homo sapiens*. Yet as a delivery mechanism for the economic flourishing of humanity now and for future generations, it is replete with deep structural flaws that must be fixed if we are to effectively address the catastrophic effects of climate change, extinction, poverty, and other converging crises.

Developing a conceptual framework for a sustainable and just economy has been a mainstay of ecological economics and related disciplines for decades, and a principal focus for the United Nations Conference on Environment and Development at its Earth Summit in 1992 and Rio+20 Summit in 2012. One of the most widely embraced frames is 'doughnut economics'.[115] It places the ideal economic system within a safe operating space between a set of planetary boundaries that cannot be breached without jeopardizing life on Earth, and a social floor of basic guarantees that ensure all humans can live decent, healthy lives.[7,116] An economy that operates within this safe zone eliminates overshoot and advances each of the Sustainable Development Goals (SDGs).

Our present patterns of consumption, production, trade and investment put us well beyond this safe zone. Holes in the ozone layer, dead zones in the oceans, CO_2 concentrations at 420 parts per million and rising, an extinction rate ten to a thousand times greater than nature's baseline rate[117] and >1.2 billion people experiencing multidimensional poverty[118] are stark reminders that we are operating well above planetary boundaries and well below even the stingiest standards of fairness and equity.

Governments, business leaders and individuals can all play roles in fixing the holes in both the ceiling and the floor. But the urgency of today's crises demands swift and decisive action by governments at all levels. Government action, if carefully planned, can provide the enabling conditions to dramatically scale up solutions offered by nonprofits and business leaders, and major lifestyle changes by individuals.

Governments have many tools in the toolbox for steering the economy: taxation and spending, monetary policy, investments, regulation, direct provision of goods and services, setting goals and targets and by establishing and enforcing the rules of engagement – the institutional arrangements that, for example, establish property rights and limits of liability.[119, 120] To solve humanity's converging crises, all these tools need to be employed to catalyze the long overdue transition to a sustainable, just and climate resilient regime. Some critical interventions include:

Replacing GDP growth with genuine progress as the primary goal of economic policy

In the past 200 years human societies turned the timeless and subsistence use of nature into an economically profitable and destructive market economy powered by FF. Half of all CO_2 from FFs has been emitted since around the time of the UN Framework Convention on Climate Change in 1992. Nature has also until recently been seen as a free source of commodities like timber, water, land, soil and fish, without respect for nature's role in providing habitats, critical resources for other species, and ecological functions and services.[40]

Solving our related and equally urgent biodiversity and ecosystem crises will be a significant part of solving our climate emergency.[16] This requires a two-pronged approach, involving immediate actions over the next decade, as well as profound but longer-term shifts in ethical, social, cultural and economic values. Since the end of World War II, gross domestic product (GDP) has been the dominant measure of economic health, although never designed for that purpose.[121] While GDP tells us important information about the level and monetary value of production, consumption, trade, government spending, and national income, it tells us little about the wellbeing of individuals, households and communities. Nor does it provide the right economic signals when we breach planetary boundaries or fall below social floors. GDP growth is celebrated even when it means growth only for the wealthiest, or when governments spend enormous sums fighting wars and dealing with climate disasters, and when households spend more on medical insurance and college tuition without improvements in health or education.

A global 'beyond GDP' movement has generated far better indicators to use to guide public budgets. These alternative economic tools analyze the costs and benefits of policy interventions and monitor economic performance.[122] One metric extensively vetted by economists – the Genuine Progress Indicator (GPI) – is gaining traction worldwide.[123, 124] GPI measures the net benefits of economic activity – benefits minus costs - instead of counting all increases in economic activity as positive. It goes well beyond GDP by assigning monetary value to nonmarket contributions important for economic wellbeing such as unpaid labor, services from both green and built infrastructure, and social benefits of education. While global GDP per capita has increased steadily, human wellbeing has stagnated or fallen since the mid-1970s.[125] Recently, federal legislation was introduced to move this metric to the forefront of economic policy making in the US.[126]

Correcting market failures through carbon and other environmental taxes

In an efficient economy, prices should reflect not only the internal costs of producing a good or providing a service, but also all external costs – like increased unemployment or climate change – that are currently passed on to society. A gradual but determined strategy toward full social cost pricing would dramatically improve market efficiency while reducing frivolous consumption. Carbon and other environmental taxes provide a remedy for chronic underpricing but remain a largely untapped tool, accounting for only 6.7% of total revenues in OECD countries.[127] Carbon taxes on all GHG polluting industries set at a credible social cost of carbon, when combined with removing subsidies for FFs and other damaging products and practices, will decelerate consumption of carbon intensive goods and services and generate badly needed revenues for funding climate adaptation. However, market prices alone are unlikely to solve the full dimensions of climate change and the degradation of nature.

Restoring natural capital and ecosystem services

The Earth's remaining natural capital and biodiversity – in wild forests, rivers, grasslands, wetlands and marine areas – provide services of immense economic value[40] to humanity, like carbon sequestration, flood control, water purification, pollination and disease control. They also provide critical sources of food and medicine in both developed and developing nations and sites for thriving tourism and recreation industries. Global estimates suggest the economic value of ecosystem services to top $125 trillion per year, nearly double that of the economic system.[128] But their degradation and loss to society at large continue as more wild areas are clearcut, paved over or polluted, to the benefit of private developers and the loss of humanity and planet. Given the immense ecological and economic returns of protecting what's left and restoring natural capital and ecosystem services where they have been lost, protection and restoration should be a strategy at the core of economic development and climate action programs at all levels of government, to prevent near-term collapse of ecosystems and dependent economies.

Relocalization

Free trade is actually not free at all. Globalized trade comes with a steep price tag. Trade exposes the world's remaining stocks of natural capital to the largest possible market of ever-wealthier consumers, thus accelerating depletion. Moreover, like many economic phenomena, trade openness is subject to the law of diminishing returns. After a certain threshold, the benefits of more and cheaper goods are outweighed by increasing costs of inequality, declining wages, community instability, brain drains, pollution and CO_2 emissions.[129, 130] At least 30% of transport sector GHG emissions are associated with international freight.[131] Relocalization – restoring socially efficient levels of local production – offers an opportunity to scale these emissions back while fostering genuine economic progress in distressed economic regions, left behind by the rush towards overspecialization and global hyper-trade. But to be successful, barriers to localization – ranging from trade agreements to export subsidies – should be phased out.

Eliminating harmful subsidies

One of the tragedies of the global economy is just how much harmful economic activity is sustained not by individual choice, but by deliberate market interventions by governments to protect and expand the market share of favored industries and corporations - regardless of social costs. For example, the US is the top global producer and consumer of wood products, and to maintain this status the industry enjoys a diverse array of large tax breaks, subsidies, and marketing assistance from the federal government and most states. Subsidies lower production costs and consumer prices, thus artificially increasing consumption. Moreover, this industry's short rotation clearcutting practices are driving climate change and making the land less resilient to its effects, including wildfire and pathogens.[48, 132] The oil and gas industry, corporate agriculture, and developers also enjoy generous subsidies. FF subsidies by themselves were found to approach $5 trillion annually by a recent International Monetary Fund (IMF) assessment, while subsidies for related sectors add at least another $1 tn.[133,134]

Land reform

An increasing share of the means of production have fallen into the hands of investor-driven corporations whose only goal is to provide maximum returns to short-term investors rather than long term-benefits to society. Nowhere is the risk of this greater than in the colonization of the world's prime farm and forestland by these investors. Were these lands managed sustainably for the long term, they could help bend the growth curve of atmospheric GHG concentrations back towards a sustainable limit of under 350 ppm. Corporate land reform laws, such as those enacted by midwestern USA states[135] to protect family farms, are badly needed to begin the process of transferring these lands back into the hands of families, indigenous communities, cooperatives, land trusts, public benefit companies and other entities whose bottom lines are consistent with regenerative agriculture and climate smart forestry solutions.

These are some of the most important interventions that regional, state/provincial, national and global governments can take to accelerate the transformation of our global economic system from a chaotic, deeply unjust and unsustainable free-for-all into a well-managed, equitable vehicle protecting and restoring climate stability and biodiversity while ensuring adequate livelihoods for all.

Yet there are material economic reforms that individuals can already demand of themselves, their governments and corporations - at local, regional, national, and global scales, including:

- Taxation and regulatory systems that ensure that prices properly reflect true environmental and social costs of products and services.
- Land rights and urban planning models that avoid perpetual land development, loss of carbon and biodiversity, and annihilation of intact wilderness.
- End of pronatalist policies designed to increase economic growth by adding additional human labor and buyers - all while automation eliminates jobs.
- Economic frameworks for profitable activities in ecosystem restoration, e.g. through managed coastal retreat and restoring degraded ecosystems;
- Densification of urban areas, multipurpose land uses, and other forms of efficiency
- A culture of sufficiency and efficiency, rather than excess and waste.

III Breaking barriers to implementation

How do we fix the proverbial car while we're driving it? Our societal structures, values and procedures are demonstrably inadequate for the task ahead. We have called for large-scale, rapid, transformative changes in our economies, societies, cultures and politics - on a timescale of almost superhuman speed. Several of us have worked intensely for many years in science-driven and evidence-based public policymaking. We are not naïve about the odds of achieving these changes - nor the difficulties of doing so within existing structures and processes of government. The public can demand farsighted leaders willing to reform political systems to resist powerful vested interests and manage the social and economic transitions associated with decisive climate action. Each of us can also work to change the culture within society as well as specific businesses and institutions to act responsibly and accelerate change. And each of us can make changes in our own behavior.

Too many current leaders are willing to risk future catastrophe when it will be another's problem.

Some of the changes needed are mundane, but require coordination across scales. Running climate change preparedness workshops with provincial and local government planners in South Africa in 2008-10, two of us realized that the difficulty of implementing transformative change was often found at the most tedious level: basic compliance, planning and budgeting processes. The civil servants in our workshops were often inspired to change, but hamstrung by *short planning horizons, performance indicators, budget cycles, restrictions on discretionary spending and on shifts between budget allocations*. All these defeated their best intentions to plan better, save money, and reduce risks. Public management processes need reform to enable rapid adaptation. This is not complex, but requires time and bold leadership. As the climate and planet cannot wait for this reform to be complete, most nations, subnational governments and business and institutions will need to invoke and monitor the success and value of temporary measures. Another immediate step would be the consultative scheduling and budgeting for priority actions and reforms.

Protest and other bottom-up demands for change and experimentation will help break through barriers and instil urgent action. Social movements, NGOs, academics, the private sector innovators all need to be part of the solution. This requires significant collaboration and social learning.[136] The youth have shown us this is possible for climate action and social justice. Communities and governments, at all scales from local to global, have the responsibility now to scale up solutions and actions in each of these areas. Scientists and others with essential expertise can work together, and with those with the moral authority to engage society in the massive cultural and economic change that is needed.

Finally: instability often brings out the worst in people, when the times require the very best. Beyond rhetoric, our leaders are obliged, especially now, to uphold the culture and principles of integrity, vision, and responsibility to future generations and others who are innocent of the destabilization of our planet. Corruption has eaten deep into humanity's moral fabric, leading to widespread environmental, social and spiritual bankruptcy. Sadly, this "corruption tsunami" is manifest in most nations: in corrupt electoral processes, questionable infrastructural development financing, abuse of the rule of law, collusion in resource extraction contracts, and stripping of the rights accorded to citizens under national constitutions and laws. We again ask, what kind of leadership and systems of governance will take us successfully into the future?

IV Conclusion

The time for empty commitments for the distant future of 2050 is over. The need for action is now.

Our challenges are less technical than social – taking the necessary actions quickly enough, in all nations and governance regimes – particularly democratic ones - while maintaining adequate social, economic and political stability to steer the ship of humanity safely into a wiser, more sustainable world order. This will require unprecedented global collaboration, social learning, and public awareness and pressure. This will profoundly challenge us all, and our systems of planning, cooperation and governance.

Over the next decade, we have a stark choice: to demonstrate the very best of our natures as *Homo sapiens* - cooperative, innovative, wise, and ethical, to learn from mistakes and create better societies - or to go down with both a bang of conflict and a whimper of bickering, entitlement and self-interest. That choice is ours. The actions or inactions of individual leaders in government, communities and businesses in this decade will be remembered darkly, or hopefully kindly. Everything we know and love is at stake.

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