14. Climate and environment: what we know and what we need to know

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Expanding welfare in a world with climate change requires meeting two fundamental challenges. First, economic growth must properly account for the damaging effects of environmental externalities. Secondly, societies need to build resilience and adapt to the changes in climate that are already upon us. In this chapter, we summarise the existing evidence on how countries can undertake these two necessary transitions. Rich or poor, big or small, these transitions apply to all countries across the world. At the same time, climate justice is pertinent, as countries or individuals most vulnerable to climate change and environmental decline are likely to have contributed least to the problem. We argue that innovation is the path through these challenges. Technological and institutional innovations can help overcome the trade-offs that make political action on the environment so difficult. While much is known, a great deal remains unclear. We lay out where researchers can support policymakers by addressing knowledge gaps that can form a new research agenda for sustainable growth.

I. Introduction

Our impact on the world's climate and biosphere is 'unequivocal'.[1] Any combination of social, economic, and moral arguments justifies a sharp departure from the status quo. Two concurrent transitions need to happen. First, expanding wellbeing while rebalancing our relationship with nature requires a fundamental overhaul in how we harness energy, produce goods, and manage natural capital. Second, those in harm's way – often the poorest – must change occupations, locations, or adopt new technologies to protect themselves. Rich or poor, big or small, these transitions apply to all countries

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across the world. In this chapter we argue that innovations, broadly defined, are the path through these two goals.

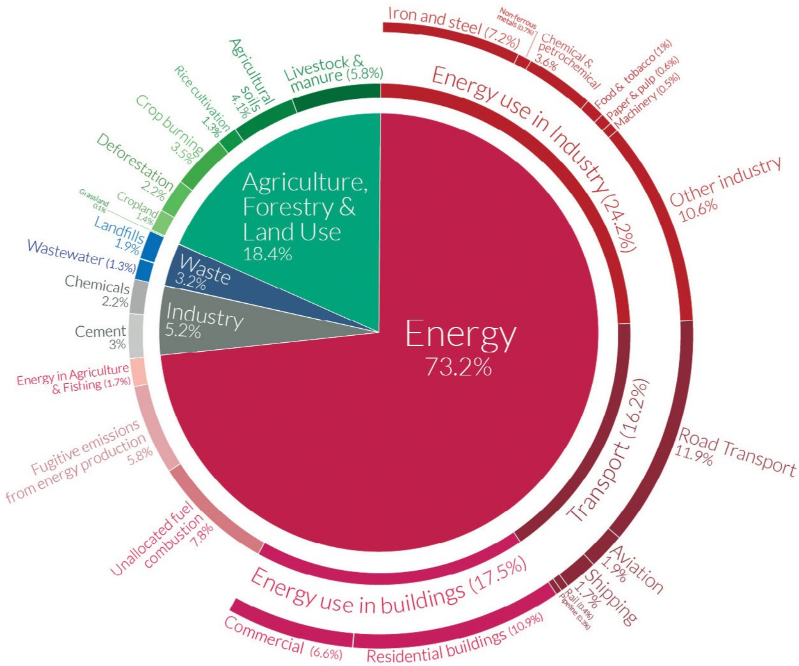
Unless our method of expanding economic activity changes, our actions will increasingly have harmful impacts in ways that we are only beginning to understand. Thus, sustainable growth, which we define as the path that delivers the maximum possible gains in human welfare after properly accounting for the damaging effects of environmental externalities, is paramount. This is especially true for today's low- and middle-income countries (LMICs), which house the majority of the world's poor, as well as those most vulnerable to climate change. Economic growth remains a political and moral imperative in these countries – but climate change and environmental degradation can slow down future economic growth and threaten essential amenities, severely reducing the potential to improve human welfare. To deliver on the promise of radically increasing the standards of living across the world, these externalities must be addressed.

Sustainable growth will need systemwide changes in how we obtain energy, produce goods, and manage our natural capital (Figure 14.1). A core component of this change involves shifting to clean sources of energy for electricity generation, such as solar or wind. More of the energy used for consumption or production also needs to be from electricity, which, in turn, should be derived from clean sources. Industrial production releases greenhouse gases (GHG) both from its energy-intensive nature, as well as the materials and inputs used in its various processes. Firms will need to switch to cleaner inputs and production processes. Lastly, we need to preserve and restore our natural capital by limiting emissions from agriculture and by lowering the stress placed on land and other natural ecosystems in the process of growth. This is especially pertinent for rapidly developing low-income countries.

The fundamental challenge, in our view, is that many of the standard economic solutions to these environmental externalities – such as carbon taxes, emission quotas, or deforestation bans – face enormous political opposition. These policies typically generate well-defined groups of losers who can organise and effectively lobby governments to block their implementation. Further, these policies are often perceived to be detrimental to economic growth or unjust in the face of historical emissions. No government will support an anti-growth agenda. Likewise, for the most vulnerable countries – often among the least developed – an adaptation imperative may take precedence over goals to minimise externalities.

We argue that innovations, be they technological or institutional, can help solve this gridlock. This is chiefly because innovation can ease the trade-offs that make political action on the environment so difficult. A clear example of this is the recent development of cheap solar energy, which makes low-emissions growth not only viable but also financially attractive. Innovation, however, will not address every tension between growth and environmental conservation, and some difficult trade-offs are likely to remain. For these, governments need to find effective ways to respond to environmental externalities.

Figure 14.1: Global greenhouse emissions by sector



Source: Hannah Ritchie (2020)2 'Sector by sector: where do global greenhouse gas emissions come from?' Our World in Data. Reproduced under CC-BY licence.
Notes: Global greenhouse gas emissions are shown for the year 2016, when they were 49.4 billion tonnnes CO_2eq.

In this chapter, we summarise the existing evidence on how countries can undertake the two necessary transitions of sustainably expanding living standards, while adapting to a world with climate change. Achieving this rests on technological and institutional innovations that (i) enable clean energy; (ii) foster clean growth; (iii) preserve and restore our natural capital; and (iv) facilitate adaptation to a warming world in a just manner. The breadth of such topics naturally creates important omissions; we focus on what we think may be some of the leading issues that have universal relevance. Within these issues, we pay special attention to today's developing economies, for both reasons of climate justice and the fact that they will be the largest drivers of future emissions.[2]

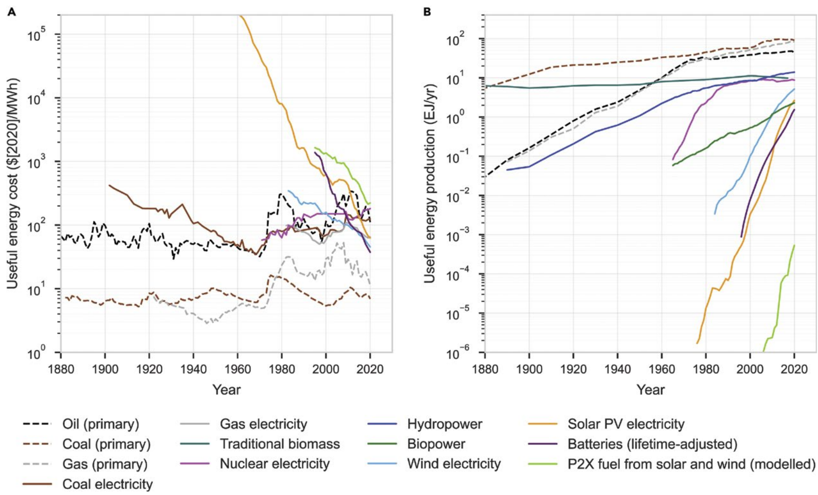
A central theme throughout our chapter is that, while much is known, a great deal remains unclear. In each section we lay out where researchers can support policymakers by generating more evidence. We make no claims of exhaustiveness, but taken together these knowledge gaps can form a new research agenda to understand the key market failures preventing innovation for sustainable growth.

II. Clean energy

Energy use, be it for consumption, production or transportation, is the single largest source of externalities. Two facts frame the following discussion: (i) the demand for energy, particularly in emerging economies, will continue to grow aggressively; and (ii) this energy must be produced cleanly if we are to minimise environmental externalities. Electricity will play an ever greater role in the global primary energy supply and is thus a central focus.

1. *What we know*

Figure 14.2: Historical costs and production of key energy supply technologies



Source: Figure 1 in Way et al. (2022),[3] reproduced under a CC-BY licence.

The demand for energy will only grow in the future. While improvements in energy efficiency might temper this increase, economic growth in developing countries will not occur without a major expansion in energy use.[4] Energy consumption per capita in LMICs is only 15% of that in high-income countries.[5] Limited access to high-quality energy has large economic and social costs in the form of lower levels of employment, firm entry, and human development outcomes, especially in the long run.[6] Expanding energy use is thus a first-order priority for developing countries.

In 2021, 71% of global electricity production was sourced from fossil fuels including oil, coal, and gas.[7] If that percentage remains the same, any great expansion in energy use will generate substantial environmental externalities. Today, however, innovation in clean energy technology has fundamentally changed the nature of this trade-off. The costs of key green technologies have fallen according to a power law based on their greater deployment

– the so-called Wright's Law.[8] Accounting for full system costs, renewables like solar or wind are now the cheapest sources of electricity ever known.[9] This makes it possible, in principle, to produce low-emissions electricity at a large scale, resulting in substantial net savings once appropriate cost declines are modelled.[10] How quickly the transition can be made towards these new technologies will determine whether we are able to mitigate emissions in time to prevent even more severe climate change.

The significant recent advances in clean energy still do not imply that the overall direction of innovation is optimal. Higher energy prices have been associated with more innovation in energy efficiency.[11] The predominant role of fossil fuels, plus the minimal pricing of negative externalities from their use, skew innovation away from clean energy.[12] Engineering breakthroughs in the extraction of shale gas, for instance, brought short-run benefits by lowering coal use but likely reduced the speed and direction of green innovation.[13] Overall, these innovation distortions are quantitatively meaningful.[14]

In the long run, the energy transition requires electrifying almost all activities that rely on combustion for energy – be it wood for cooking, fuel for cars, or coal for boilers – and producing this electricity cleanly.[15] Along the way, improvements in energy efficiency, like adopting more efficient cook stoves or LED lighting, can make significant contributions towards flattening the trade-off between emissions and growth. Even for activities that do not require electricity, new technologies are allowing individuals to consume more while polluting less. For example, clean fuels for cooking and heating substantially improve household air quality, lowering morbidity and mortality, and curb deforestation.

A broad class of constraints slow down the diffusion of clean energy: (i) weak incentives resulting from distorted price mechanisms; (ii) poor information; (iii) adoption risks (including leakage) and high cost of capital; (iv) lack of a trained workforce; (v) infrastructure; and (vi) other legal and regulatory hurdles, for example, regarding land acquisition or permitting.

Poor transmission infrastructure and intermittency can slow the uptake of renewables. This is amplified in countries that have large swings between peak and off-peak electricity consumption. Intermittency becomes a larger challenge as the penetration of renewables in the electricity mix grows.[16] Handling these issues will require significant investments to expand grid capacity and interconnections, improve grid management systems, and introduce new incentive mechanisms to ensure timely dispatch. Over time, as battery prices fall, grid storage systems can be connected.

Furthermore, clean energy is often produced in scarcely populated areas, such as deserts, which are not currently connected to the grid.[17] The locations of generation, such as offshore wind, do not typically overlap with main demand centres, which can create congestion within the transmission system. A commensurate expansion in the transmission network – both in terms of reach and capacity – will be required to realise the gains in clean energy innovation.[18]

Fortunately, policies and investments can help lift these barriers. Where private actors are involved in energy generation, there must be clear economic returns to expanding clean energy generation capacity. This may involve subsidies that compensate private actors for start-up and infrastructure costs, and feed-in-tariffs that limit the risks of adoption. Feed-in-tariffs were a key part of Germany's policy to foster the development of solar electricity, while China used production and innovation subsidies to support its nascent solar energy sector.[19] The Inflation Reduction Act marked an initial foray into channelling large amounts of subsidies and support relating to energy and climate change in the US, though recent political changes make its future increasingly uncertain. The state may also have a key role to play in training the workforce with non-general skills, and those specific to the large-scale adoption of clean energy technologies.[20] The familiar economic ideas of gains from trade arising from enhanced market access and integration apply to the diffusion of energy: in Chile, for example, the expansion of transmission infrastructure sparked considerable private entry in upstream production markets, especially in renewables.[21]

Well-performing energy markets can also speed up the diffusion of new innovations. However, in most low and middle-income countries, genuine markets for producing and selling electricity do not exist. Instead, there is a reliance on fixed long-term contracts for procuring energy. While playing an important role in risk reduction, such contracts are often not competitively awarded, which risks locking in disadvantageous terms. Neither can they be easily exited, complicating the path for cheaper and cleaner alternatives like solar or wind to enter. The movement towards wholesale markets for electricity production, where plants bid against each other to supply power at frequent intervals (e.g., daily), opens up more opportunities for new technologies to displace old ones.

Lastly, energy usage is fundamentally misallocated in several countries.[22] The core source of misallocation is the disconnect between prices and social marginal costs. Where energy retail is organised by the state, this may require lifting some indiscriminate subsidies, while providing some additional support for the poorest households. In low- and middle-income countries, additional complications of non-payment and outright theft of energy arise. The presence of high subsidies and weak enforcement of payments, coupled with political pressure, keeps energy prices far below costs in much of the world. This forces utilities to run at a loss and makes it impossible to fund investment in a high-quality diffusion infrastructure.[23] Overall, energy is not systematically allocated to those who have the highest marginal willingness to pay for it. Where energy retail has been privatised, fostering competition among private retailers is also essential to unleash the full benefits from privatisation. Even with private competition, independent regulators are necessary to ensure consumers are not unduly affected.

2. *What we need to know*

Continued innovation in clean energy will further drive down costs and help diffuse these technologies. But, at the same time, continued investments into exploration and innovation in fossil fuels is taking place. Will the market process get the direction of innovation right?[24] Understanding where and how state intervention is needed (beyond the standard subsidising of research and development (R&D) to account for positive knowledge externalities) remains an important area of research. There is some evidence that policies aimed at curbing emissions, such as an emissions trading scheme, increase low-carbon patenting.[25] However, we still need more direct evidence on what types of policies best encourage innovation in clean energy. This can build on top of the wider literature on the impact of innovation policies.[26]

Next, we need a better grasp of the dual challenges of intermittency and grid infrastructure in inhibiting the uptake of clean energy. Even accounting for system costs from intermittency, wind power in Spain generated an increase in consumer welfare.[27] The gains, however, are heterogenous, and negatively impact non-wind power producers. More evidence on the impacts of intermittency on consumers, producers, grid stability, market outcomes, and investment is critical as penetration rates increase. Likewise, disparate and limited grid networks pose an immediate block on expanding clean energy. In some areas of the US, for example, wholesale electricity prices are now negative for 20% of all hours as excess power generation is trapped in a constrained grid.[28] We need to know more about how grid investments can be financed, but also how policies and regulations need to be adjusted to allow for more integrated networks and the timely construction of new lines.

It is also important to consider how fossil fuel energy production will respond to the expansion of renewables. There is a risk, in particular, that clean energy will displace gas proportionally more than coal. As burning coal produces more emissions than burning gas, it may be possible to obtain further gains in emission reductions by providing incentives for energy producers to discontinue coal rather than gas. Auctions for phasing out coal plants, such as those seen in Germany, are being looked at as possible mechanisms for ensuring a timely exit from coal.[29] These auctions, or any policy aimed at the same outcome, will have to be careful in their design to ensure additionality – that they result in greater carbon reductions than would otherwise have been the case.

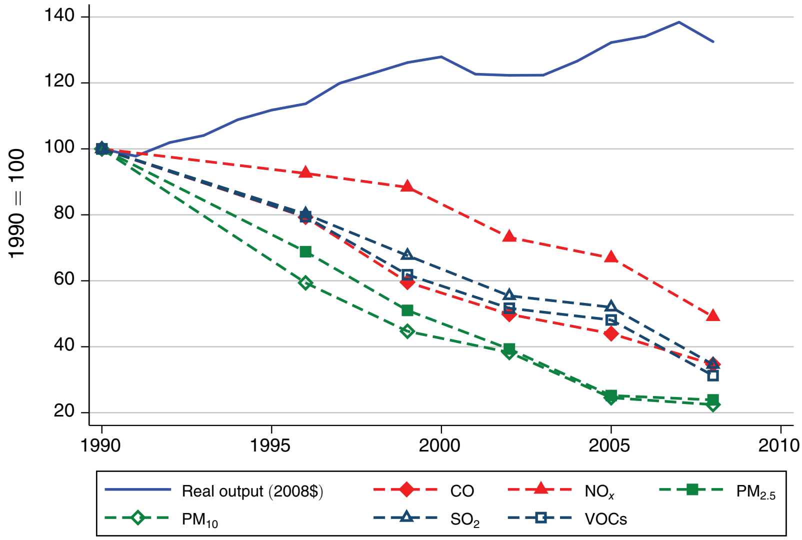
Reforming energy markets and introducing more wholesale competition is a complex institutional endeavour that takes years or decades of planning. This includes setting up markets for emissions. An important area of research is how markets for electricity production can help deliver welfare gains for society through cheaper costs, as well as the adoption of the latest and cleanest forms of production. While these gains may seem obvious on paper, they may be limited in practice by the emergence of monopoly power or collusion. For example, recent evidence from Colombia exposes how the prevalence of collusive practices between energy producers in a privatised market drove up consumer prices.[30]

III. Clean growth

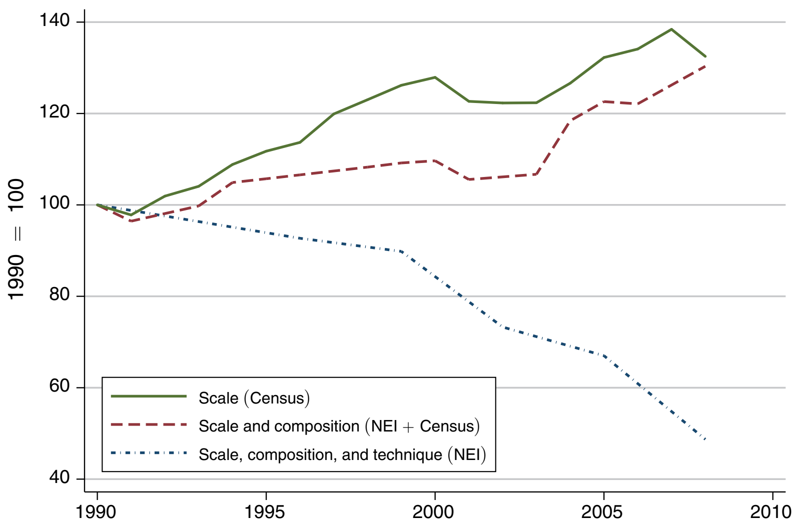
1. *What we know*

Figure 14.3: The decline of externalities from manufacturing production in the United States

a) Trends in manufacturing pollution emissions and real output



b) Nitrogen oxides emissions from manufacturing



Source: Figures 1 and 3 in Shapiro and Walker (2018).[31] Copyright American Economic Association; reproduced with permission of the *American Economic Review*.

As economies grow, firms expand and adopt new technologies. Wage labour in complex organisations becomes increasingly predominant. Better technologies and better workers raise productivity, boosting their earnings and living standards. During this process, however, many firms also generate substantial environmental externalities. This is the challenge that must be overcome.

A combination of technological innovations in production and regulation have lowered pollution from manufacturing without lowering production.[32] However, while GHG emissions have been declining or plateauing in the European Union, they are on the rise in LMICs.[33] Industries such as cement manufacturing are massive emitters: by one estimate, cement manufacturing alone contributes 8% of global emissions.[34] China's cement production emits around 850 million tonnes of CO2 each year; the total of all low-income country emissions is a mere 200 million tonnes. All of Africa emits 1.4 billion tonnes.[35] Firms are also responsible for a significant amount of air and water pollution. Approximately 40% of PM2.5, the finest form of particulate matter with a diameter smaller than 2.5 micrometers, in Sub-Saharan Africa can be attributed to the combustion of fossil fuels for energy and industry, while the misuse of nitrogen-based fertiliser by agricultural firms has driven freshwater eutrophication.[36]

The development of large, technologically advanced firms offers several sustainable growth opportunities. First, these firms are better placed to mitigate environmental externalities through innovation compared to smaller, less productive firms. For example, large firms can more easily electrify production and adopt other effective pollution reduction measures. Smaller firms face more constraints in making these investments. Second, larger firms, especially those with multinational linkages, are likely to be more resilient to environmental shocks. This protection can be both physical – e.g., when jobs are performed indoors in safe environments – and economic. Since these firms are better integrated with markets, they can easily access credit, and are potentially less sensitive to climatic shocks. Their multinational linkages may also make them yield to pressure to green their own supply chains.

The market failures that inhibit innovation in clean energy also stymie green innovation in production. The standard optimal policy combines two separate tools: R&D subsidies to spur green innovation, and a tax on the negative environmental externality, e.g., a carbon tax. As of 2023, 37 carbon tax schemes exist around the world, covering only about 6% of global GHG emissions.[37] Note that these schemes extend beyond electricity generation and touch large-emitting industries. However, in many cases such policies are not feasible. Instead, alternative policies and broader interventions will be necessary. One alternative is a cap-and-trade system, where the government caps the total amount of emissions allowed by a sector or geography, but lets firms trade emissions permits. Cap-and-trade systems are attractive as they do not require governments to commit to a particular price for emissions. However, they are often more complex to establish than a tax set by the government, and, in the case of CO2 emissions, they have not been able to deliver carbon prices anywhere near the estimated social cost of carbon.[38] Industrial policy for strategic sectors or activities that have the potential to generate clean growth has also garnered recent attention, especially given the lower public aversion to the policy.[39]

The regulation of production is another central tool to address externalities. Governments can regulate externalities by setting standards or individual quotas on pollution or emissions. Examples of this include fuel efficiency standards in automobiles and pollution quotas. The global nature of the externality, however, alters not only private actors' incentives to pollute but also governments' incentives to regulate the externalities from production. Economists have examined various potential solutions to the collective action problem facing regulators. Some have investigated whether trade policy can curb environmental degradation, or whether climate clubs can induce emission abatement by imposing trade penalties on non-members.[40] Others have considered the role of the contractability of green investments, or the role of intellectual property rights for green technologies and the duration and stringency of climate agreements in facilitating cooperation.[41]

Unilaterally implementing green regulation does, however, raise concerns about carbon leakage: businesses transferring production to countries with laxer emission constraints. That said, empirical studies have yet to find significant evidence of leakage, perhaps because key industrial sectors are often shielded by policymakers.[42] This may not be the case in the future. A final concern is that uncoordinated policies designed to mitigate emissions in developed countries may have adverse consequences for production in less developed economies.

Trade may have a particularly important role in moderating the damages from climate change, as the impacts of climate change are projected to be highly heterogeneous across locations and sectors. The literature has produced a set of nuanced findings on this point, and it remains an active area of investigation. Trade can lower the price volatility of agricultural goods following weather shocks; when combined with risk mitigation technologies, this can raise overall farmer welfare. One paper argues that, due to high trade barriers, the low-income countries that will be most affected by climate change will specialise more in food production, despite the fact that climate change will decrease the productivity of agriculture by more than it will affect the productivity of manufacturing.[43] Their model suggests that increasing trade openness will result in a major reduction in the cost of climate change in poor economies. A separate analysis showed that, while climate change will alter the relative productivity of different crops across space, trade will play an important role in the reallocation of plots to the most productive crops.[44] Exploiting this 'evolving comparative advantage' can greatly diminish the aggregate welfare effects of climate change.

2. *What we need to know*

The primary question is how production can be made cleaner without harming economic performance. Answering this requires more evidence on at least three complementary policy areas: promoting green innovation in firms; skills and matching policy as climate change intensifies and during the green transition; and trade policy to maximise the benefits from green comparative advantage.

Concerning green innovation, a fundamental question is whether carbon taxes, or something like them, are politically viable, especially if they harm growth, have negative distributional effects, or if they may be unjust with respect to historical emissions. A related question is over whether to target innovation subsidies to specific sectors or technologies, even within green sectors or technologies, especially if there are knowledge or technological spillovers. Lastly, it remains valuable to consider how policy should change in a dynamic world where there are first-mover advantages (e.g., 'winning the green race') or where a clear end date to an industry is mandated (e.g., net zero by 2050). Understanding how such policies can be designed or communicated in a palatable way is a crucial area for more evidence.

More evidence on the important ingredients for successful industrial policy is required. For example, China provided local demand subsidies to support its solar sector, but these were less effective compared to production and innovation subsidies.[45] India introduced local content requirements to boost demand for local firms involved in the solar energy value chain, but the policy failed to ignite domestic growth in the sector due to its flawed design.[46] Both shortcomings require explanation.

It is unclear to what extent economies lack the skills to adopt green innovations in production. If a lack of skills keeps individuals in occupations that damage the environment, skills programmes may also have positive benefits for the environment. In addition to skills in sectors that reduce emissions, more thought should be given to the role of training and other skills programmes in creating opportunities for adaptation and resilience, such as providing skills that create more opportunities for non-agricultural work. More generally, as climate change intensifies there may be a growing mismatch between the supply of human capital entering a local labour market and the demand for it. Left unaddressed, these imbalances could impede the ability for individuals to find suitable opportunities. In fact, job search and matching is an area where policy intervention may be beneficial. Firms face significant search frictions, especially in developing countries, when trying to hire the workers they need. Such issues are pertinent if we expect large-scale reallocation of labour across occupations, sectors, and locations due to climate change and the accompanying green transition. The ability of an area or sector to absorb additional labour matters for evaluating the opportunities for local adaptation and to better understand the welfare effects of policies aimed at curtailing environmental externalities.

Finally, we require more evidence on the extent of and remedies to carbon leakage as governments implement more ambitious mitigation policies. Aside from avoiding leakage, international cooperation could in fact further facilitate achieving emissions reductions as efficiently as possible: since LMICs offer particularly cost-effective opportunities to save GHG emissions, financing climate projects in developing countries could accelerate mitigation efforts at current spending levels. More research on how this cooperation can be organised and designed effectively, as well as on how climate change mitigation projects can boost development, is urgently needed. Concerning trade policy, LMICs will also have to adapt to changes in trade policy implemented in rich economies, in particular via mechanisms such as carbon border adjustments. The EU has recently developed a plan for a regional carbon border adjustment mechanism, which would require importers without equivalent carbon prices to buy carbon credits to cover the carbon cost of goods procured.[47] Understanding the full impacts of border carbon adjustment policies in developing countries is a research area of first-order importance.

IV. Natural capital

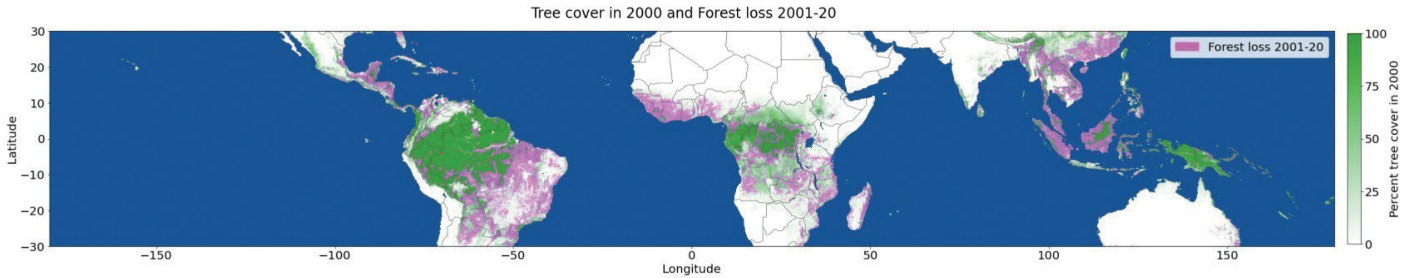
1. *What we know*

Natural capital is vital for continued economic development. Consider vultures: a keystone species in India, their population collapse led to an increase in water-borne diseases, producing mortality impacts on the same order of magnitude as those expected from excess heat by the end of the century.[48] Allowing the stock of natural capital to collapse, as it has been doing in recent decades, is exposing us to myriad risks that we are only just beginning to understand.[49]

The collapse is happening along multiple dimensions. We are witnessing the sixth great historical extinction of species on Earth.[50] Global coverage of living coral has fallen by more than half since the mid-20th century, greatly compromising the services they provide to society, such as food and coastal protection.[51] The diminishing quality of soil, water resources, and forest ecosystems is well documented.[52] Deforestation continues at an alarming pace: subtropical forest loss doubled during the 21st century, and the rate of global forest cover loss increased in every region (except Brazil) from 2000 to 2012.[53]

Advances in monitoring technologies have provided greater resolution and precision on the scale of natural capital loss. Remote-sensing products can now detect land use changes at very fine levels of aggregation.[54] Such techniques have been employed to assess the use of fire for land clearing and its associated negative externalities in Indonesia.[55] Likewise, they have been used to document both the improvement and subsequent reversal of deforestation rates over the past two decades in the Brazilian Amazon as policy regimes changed.[56]

Figure 14.4: Tropical forest loss in the past two decades



Source: Figure 2 in Balboni et al. (2023),[57] reproduced under a Creative Commons Attribution 4.0 International License.

Conservation policies have been the traditional go-to policy for reducing environmental degradation. This includes, for example, the creation of protected areas for old growth forests, savannahs, or coastal wetlands. Conservation efforts are designed to maintain the critical functions of these ecosystems – habitat provision, carbon sequestration, adaptive benefits, and other environmental services. But the efficacy of conservation programmes continues to be a contested topic in both environmental management and economics literature. Focusing on the economics, evidence on whether conservation programmes reduce poverty at both the local and macro-level is inconclusive.[58]

Several other policies have been deployed but with mixed results, or without rigorous assessment. Take payments for ecosystem services: they have shown clear benefits, for example, in the case of deforestation, but overall, the evidence on their performance is mixed.[59] Another set of policies focuses on strengthening property rights, for example, through land titling: they too have had mixed results.[60] Meanwhile conservation interventions, such as rewilding, may hold promise to protect biodiversity, but rigorous evidence on their impact is largely missing.

Lastly, a clear grasp of economic and political incentives remains critical to design feasible policies for natural capital management. For example, consider the central tension between government, firms, and citizens to exploit forests and convert land for other uses: a global imperative (climate change) may compel the national government to preserve the forest; local firms may be driven by a desire for rent extraction; and individuals may lack attractive economic alternatives that disincentivise deforestation. Indeed, for countries like Indonesia, Brazil, and the Democratic Republic of Congo, the exploitation of forest land is critical to national development. Thus, there is an urgent need to devise effective policies that balance local development and global conservation objectives.

Overall, the knowledge of scientists and local communities is essential for designing and implementing policies to bolster natural capital. The former can help identify priorities in the face of highly complex systems by pointing to the relevant keystone species, threshold effects, or emissions contributions. The latter will know about their local ecology and the importance of different natural resources in their daily lives. Economists can contribute by bringing the two together.

2. *What we need to know*

While the problem is clear, there is still a substantial evidence gap on how best to integrate natural capital into policy. Evidence is needed in two overarching areas. The first relates to improving our measurements of natural capital and the benefits and costs of conservation. Central to this is the continued efforts of scientists to capture the drivers and impacts of natural capital loss. The second relates to designing and evaluating policies to manage natural capital, taking into account how the distribution of costs and benefits overlaps between stakeholders and geographies.

Conserving natural capital generates winners and losers. A large portion of the benefits of these resources are external to the populations that live close to them and can profit from their depletion. This creates bottlenecks. How these conflicts or coordination failures can be overcome is a key area for more evidence. An element of this relates to better measuring the economic and environmental impacts of proposed interventions. In most cases, the benefits are not restricted to local users, nor spread evenly in an area, and the threats can come from inside as well as outside. These are the instances where careful research on the design and evaluation of markets, institutions, and transfers for managing natural capital is still needed.

Understanding the value of natural capital and who benefits from it does not guarantee sustainable use. Institutions and markets must create the right conditions and incentives for conservation. Even for relatively well-tested programmes, such as PES (payments for ecosystem services), there is still a need for more evidence on when and why these interventions generate additionality and sustained impacts. Identifying alternative incentive schemes that ensure cost-effective natural capital protection in local communities remains a priority.

Many of the world's natural resources are in settings that are governed under limited state capacity. It is therefore likely that some will have to be given priority over others. Services can be derived from a number of environmental assets including biodiversity, forests, and water, all of which have high economic value with low substitutability. More research is needed on valuing natural resources using accurate methods, especially those that are well-suited for LMICs, to help prioritise interventions.

V. Adaptation and climate justice

1. *What we know*

Climate change and extreme weather events will have large negative effects on outcomes like income and mortality. These effects can transmit across space via supply relationships or migration, and persist across time, including in some instances for decades.[61] While households and firms benefit from a variety of adaptation measures – financial products, new technologies, mobility, and government policies – these are seldom able to mitigate the impacts of climate change completely, indicating that policies to facilitate adaptation will likely have large welfare gains. Innovative policies and strategies, both public and private, to enhance adaptation to climate change are thus urgently needed.

The central premise is that occupations, technologies, and locations of residence and work all need to shift to account for a world with climate change. Numerous dimensions, from institutions to geography to income, determine a community's exposure to climate change. Hence, there are

Figure 14.5: Mortality effects of climate change

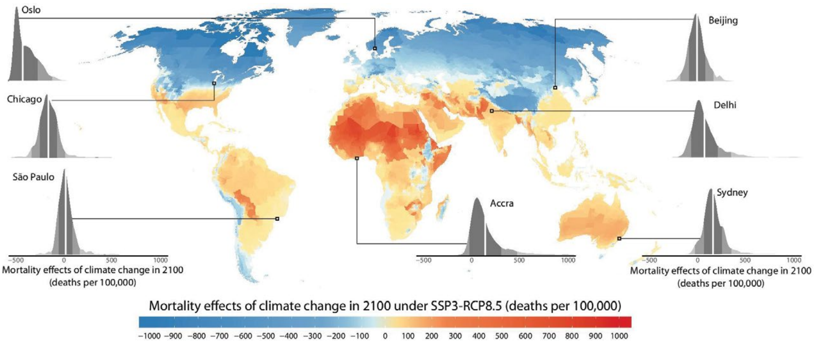


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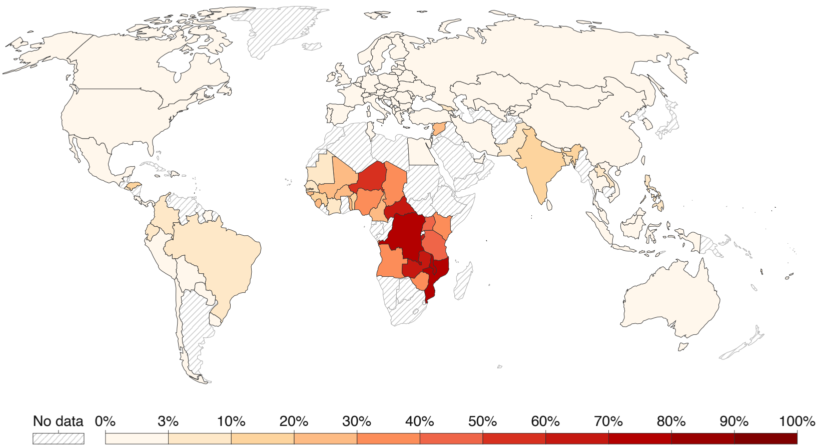
Figure 14.6: Percentage of individuals living below $2.15 a day, 2023



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multiple, overlapping barriers to adaptation. For some households and firms, the absence of insurance may be a key constraint. In other cases, access to liquidity may be the most important barrier, especially in the aftermath of a major shock, or to cover upfront adaptation costs. A lack of information about new technologies and practices, such as how improved seed varieties offer higher yields and greater tolerance to droughts or floods, may hinder climate resilience. Funds flowing into communities to assist in climate adaptation need to be curated towards relaxing the tightest local constraints. For some settings, the primary challenge may be obvious, e.g., sea level rise in small-island states. For most, however, it is far less clear what the most impactful intervention point is.

The problem of measuring and enhancing climate adaptation is complicated by the fact that climate change manifests not only via a 'falling floor' (e.g., the gradual increase in global temperatures causes lower crop yields and lower firm and worker productivity), but it also brings an increase in the likelihood of uncommon, but extremely costly events.[62] Take, for example, the devastation wrought by Hurricane Katrina in the southern United States in 2005, or the 2004 Boxing Day tsunami in southeast Asia. Such environmental damages can reverse welfare gains. In the long run, capital will migrate out of climate-impacted areas if they are unable to insure against climate shocks.[63] This calls for a major expansion and reform of support for policies and investments to deal with the new risks that climate change poses. The principal idea underpinning climate adaptation is the adoption of innovations that increase productivity and reduce the risk for households and firms. Only in this way can we continue to expand welfare and confront climate change.

Social programmes can also protect individuals against shocks. Cash transfers, unemployment insurance, ultra-poor graduation, and work guarantees have been shown to boost consumption and psychological wellbeing, especially in the face of shocks. Today, these programmes cover an estimated 2.5 billion people worldwide.[64] In LMICs, 46% of the population receives some form of social assistance. However, coverage remains limited in low-income countries, where only 15% of the population receive social protection.[65] Environmental externalities and climate hazards make the expansion of social protection more urgent. This applies to both low-income countries and vulnerable groups in richer countries. Agricultural, health, and job-loss risks are all likely to become more pronounced due to climate change. Climate change could slow down progress towards poverty elimination. In the face of these challenges, an expanded social assistance system will be essential. For example, a study in Nicaragua shows that augmenting a conditional cash transfer with either a business loan or a vocational training product enabled beneficiary households to diversify their income streams and to become more resilient to climate shocks.[66]

Climate justice is also a central issue for adaptation. The uneven distribution of pollution and damages is a major concern. The least developed countries have made minimal contributions to global externalities, yet remain highly vulnerable and are also least able to prepare for, and respond to, natural disasters. This creates an ethical imperative to redistribute resources from high-income to LMICs for adaptation and resilience. Middle-income countries can use a combination of international financing and local public–private financing to cover adaptive investments.

International coordination on climate finance for adaptation and loss and damage is at the heart of climate justice. This should be additional to, and separate from, the necessary financing to support mitigation in these contexts. Important progress has recently been made in this area: for example, COP28 initiated the long-awaited operationalisation of a loss and damage fund.[67]

Climate justice issues also occur within countries. For example, there are significant disparities in exposure to environmental externalities like water or air pollution in the US.[68] Understanding the source of these disparities requires uncovering how exposure correlates with socioeconomic factors like income, occupation, and location. As a result, regulations designed to limit overall pollution levels may have unequal impacts on different subgroups. The Clean Air Act in the US helped lower the racial gap in PM2.5 exposure through its greater impacts in larger urban areas.[69] This speaks to the need for targeted policies and investments for environmental justice even within advanced economies.

Economic research is already contributing to such investigations, for example, by pointing out pitfalls of spending and adaptation policies in the face of rising sea levels.[70] Similarly, estimates of the costs inflicted by natural disasters can inform the timing and amount of funds to be disbursed.[71] Finally, an ample literature investigates how public policy can effectively target the poor and vulnerable.[72]

2. *What we need to know*

We need more evidence on the relative effectiveness of different programmes in reducing vulnerability to environmental externalities. The key challenge will be to develop interventions that complement rather than substitute individual and community efforts to adapt to climate change. For example, social protection programmes with non-portable benefits implicitly incentivise individuals to remain in areas affected by climate shocks. Improving portability will unlock further benefits by allowing individuals to use social protection to fund migration towards less vulnerable areas. Additionally, it may be useful to design programmes that are conditional on certain kinds of behaviour that generate long-term adaptation gains (in the same way that conditional cash transfers have been used to promote human capital accumulation). The timing of assistance may also be crucial: support ahead of a predicted shock may enable households to engage in a host of adaptive responses that would not be possible if support was only given after the event. We also know very little about how adaptation constraints interact with one another. Often, multiple market failures inhibit migration from climate vulnerable areas or induce sub-optimal crop choices. For many local communities, it is therefore unclear what the most immediately effective set of interventions for protecting against climate change would be. Broad principles, such as enhancing productivity while minimising risks, can still guide the search for these points, but the need for greater empirical evidence on promising innovations remains.

Even once constraints are identified, there is much we can learn on how best to deliver support. Relative to past efforts targeting the poor, in this case the set of affected individuals may be far higher, making scalable methods critical. Future research could build on the insights of the literature on policy targeting, exploring which mechanisms best channel funding to the most vulnerable communities. Existing literature has provided evidence on the effectiveness of specific targeting mechanisms, such as proxy means testing, community targeting, and self-selection methods.[73] It will be important to understand whether these methods succeed in identifying those individuals that are most vulnerable to climate shocks. Once identified, the modality of support needs to be considered: in kind, cash, vouchers, etc. Cash has higher fungibility, but may generate inflation in communities poorly integrated with outside markets, and may expose households to considerable consumption risk determined by price volatility – a point that will become more salient in the future due to climate change. Whether this affects the ultimate balance of costs and benefits of the different support modalities is currently unclear.

The literature has emphasised the importance of general equilibrium effects, and climate hazards have major negative equilibrium impacts on affected localities.[74] Whether social protection programmes, rolled out at scale, can counteract these negative equilibrium impacts remains a key open question.

How we can effectively address climate justice concerns requires more evidence. Research can continue to play a role in providing evidence for the design of financing mechanisms to support the vulnerable, for example, by identifying effective adaptive measures for slow-onset events, or by improving measurements of the magnitude of local climate damages. To keep donors convinced of the utility of providing climate finance, implementers will need to document the use and impact of these funds. Governments should pilot, refine, test, and evaluate investments to make the case to donor countries that climate spending can support climate adaptation and mitigation.

Finally, the international dimension of climate change complicates policy and represents an important area of research. We need innovative approaches to break deadlocks in international climate diplomacy, especially on issues related to adaptation finance and loss and damage. Advances in attributing particular weather events to climate change have been helpful in laying a factual base for discussions on compensation. Much more evidence and thinking will be needed to quantify just or adequate compensation for particular events and to determine on whom, and to what degree, the burden of compensation falls.

VI. Conclusion

Expanding welfare in a world with climate change requires meeting two fundamental challenges. First, economic growth must liberate itself from generating harmful environmental externalities. Based on the composition of environmental externalities today, this will require the rapid uptake of clean energy, the introduction of green production processes, and a systematic rebalancing of how we manage natural capital. Second, societies need to build resilience and adapt to the changes in climate that are already upon us. The countries or individuals most vulnerable to climate change and environmental decline are typically those in the lowest income deciles. They are also likely to have contributed least to the problem. These factors make climate justice a pertinent aspect of the adaptation problem and call for substantial outside financing and support.

The path through these two challenges is innovation. New technologies, policies and regulatory frameworks are opening opportunities for sustainable growth that were previously deemed out of reach. Technological innovations have slashed the costs of renewable energy. Institutional innovations have enabled markets for emissions to emerge, creating incentives for firms to internalise environmental damages. Innovations in the design of social protection programmes are better equipping the most vulnerable to be resilient in the face of worsening shocks. We therefore know that there are promising innovations that can make sustainable growth a reality.

The existence of such innovations does not guarantee their timely diffusion. Classic market failures slow down the rate of innovation. Coordination problems distort investments to adopt new technologies. Incomplete information and imperfect enforcement weaken our ability to manage our natural capital. On several dimensions, such as clean energy, the diffusion of existing innovations is on par with the need for further breakthrough innovation. Markets may eventually guarantee their spread, but governments can play an active role in speeding up their deployment around the world.

While there is much that we do know, there is as much that we still need to learn. The precise way our global climate is changing, and how these changes will affect our daily economic lives, is still evolving. How we can coordinate investments to transform the existing paradigm for producing energy and goods within a condensed timeline is an open question. We also need greater insights into how we can design incentives for conserving and restoring nature in a just way, especially involving international transfers.

These unknowns have created an important space for research and evidence. The systemwide changes in question call for widespread interaction across disciplines and the fields within them. Economists, engineers and ecologists can all bring valuable tools and methods to help identify and implement innovations for sustainable growth.

Notes

1 Pörtner et al. (2022).

2 Ritchie (2020).

3 Way et al. (2022).

4 Steinbuks and Foster (2010); Lee et al. (2020).

5 Ritchie et al. (2022).

6 Dinkelman (2011); Allcott (2018); Lipscomb et al. (2013); Fried and Lagakos (2023).

7 Ritchie et al. (2022).

8 Wright (1936/2012).

9 Way et al. (2022).

10 Popp (2010); Itskos et al. (2016); IRENA (2017); Burgess et al. (2023).

11 Popp (2002).

12 Acemoglu et al. (2012); Acemoglu et al. (2016); Aghion et al. (2016).

13 Acemoglu et al. (2023).

14 Acemoglu (2023).

15 For the subset of hard-to-decarbonise sectors, such as producing steel or cement, other technologies may be necessary.

16 For countries with minimal existing renewable electricity generation, this may pose a challenge only in the future.

17 Fowlie and Reguant (2018); Gonzales et al. (2023).

18 Davis et al. (2023).

19 Banares-Sanchez et al. (2023).

20 Wasmer (2006).

21 Gonzales et al. (2023).

22 Burgess et al. (2020).

23 McRae (2015); Allcott et al. (2016); Fried and Lagakos (2023).

24 Acemoglu (2023).

25 Calel and Dechezleprêtre (2016).

26 Bloom et al. (2019).

27 Petersen et al. (2024).

28 Davis et al. (2023).

29 Jewell et al. (2019).

30 Bernasconi et al. (2023).

31 Shapiro and Walker (2018).

32 Shapiro and Walker (2018).

33 Ritchie et al. (2020).

34 Lehne and Preston (2018).

35 Friedlingstein et al. (2022).

[36] Brauer (2022); Damania et al. (2019).

[37] Metcalf (2021); Timilsina (2022).

[38] Metcalf (2021).

[39] Rodrik (2014).

[40] Hsiao (2024); Farrokhi and Lashkaripour (2022).

[41] Battaglini and Harstad (2016).

[42] Branger and Quirion (2013); Grubb et al. (2022).

[43] Nath (2025).

[44] Costinot et al. (2016).

[45] Banares-Sanchez et al. (2023).

[46] Harrison et al. (2017).

[47] Grubb et al. (2022).

[48] Frank and Sudarshan (2023).

[49] Pörtner et al. (2022).

[50] Kolbert (2014).

[51] De'ath et al. (2012); Eddy et al. (2021).

[52] Dasgupta (2021).

[53] Feng et al. (2022); Hansen et al. (2013).

[54] Hansen et al. (2013).

[55] Balboni et al. (2023).

[56] Burgess et al. (2022).

[57] Balboni et al. (2023).

[58] Adams et al. (2004); Andam et al. (2010); Naidoo et al. (2019).

[59] Pattanayak et al. (2010); Jayachandran (2022).

[60] BenYishay et al. (2017); Jayachandran (2022); Holland et al. (2022).

[61] Kala et al. (2023).

[62] Weitzman (2011).

[63] Albert et al. (2021).

[64] Banerjee et al. (2022).

[65] Division, United Nations Statistics (2020); Parekh and Bandiera (2020).

[66] Macours et al. (2012).

[67] Abnett et al. (2023).

[68] Fowlie et al. (2020).

[69] Currie et al. (2023).

[70] Balboni (2019); Hsiao (2023).

[71] Anttila-Hughes and Hsiang (2013).

[72] For example, Hanna and Olken (2018); Alatas et al. (2012); Alderman (2002); Alatas et al. (2016a); Banerjee et al. (2018).

[73] For example, Alatas (2011); Alatas et al. (2012; 2016b); Premand and Schnitzer (2020); Blattman and Ralston (2015).

[74] For example, Muralidharan et al. (2023); Imbert and Papp (2015); Egger et al. (2019); Bustos et al. (2016); Jedwab et al. (2021).

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