Ecosystem tipping points: Understanding risks to the economy and financial system

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ECOSYSTEM TIPPING POINTS: UNDERSTANDING RISKS TO THE ECONOMY AND FINANCIAL SYSTEM

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Contents

Summary

- Stable natural ecosystems underpin all economic activity. Ecosystems provide the natural resources needed for production; regulate climate change and global rainfall patterns; and provide resilience against natural disasters and the extremes brought on by global warming.
- Pressures on nature from human activity – such as land use change and pollution, as well as climate change - are increasing the risk of terrestrial 'ecosystem tipping points' (ETPs): non-linear, self-amplifying and irreversible changes in ecosystem states that can occur rapidly and on a large scale.
- Key ETPs that could threaten Earth system stability include: the dieback of the Amazon rainforest into a non-forested state; transitions in boreal forest cover; tropical peatland collapse; coral reef die-off to marine deserts; and mangroves dying back to tidal flats. ETPs will compromise the multidimensional services provided by these ecosystems to the economy.
- A key global consequence of ETPs is their feedback effect on climate change. The Amazon rainforest, tropical peatlands and mangroves currently sequester around 220 gigatons of carbon – the equivalent of around 20 years of global CO_2 emissions based on current rates - that could be destabilised, making staying below global warming of 1.5°C impossible.
- Losing these critical ecosystems will severely impact the economy through: reduced food and energy security; damages to assets such as real estate, croplands and infrastructure; and health risks that impair household productivity. The direct impacts of ETPs can reverberate globally and extend far beyond the regions where these ecosystems are located.
- By damaging the financial positions of households, businesses and governments, economic losses from ETPs can transmit to financial institutions of all types through increased default rates, collateral value declines, market volatility, insured losses and inflation shocks.
- ETPs will result in large-scale nature degradation that limits adaptation and substitution possibilities, increasing the likelihood that economic and financial risks will be systemic. The time horizon for impacts from

ETPs could be more immediate than those from physical climate risks. Collapse of these ecosystems thus represents worst-case scenarios or 'tail risks' from nature loss.

- Financial and macroeconomic policymakers such as central banks and financial supervisors, as well as ministries of finance, thus need to prioritise these ecosystems when assessing nature-related risks. The ecological aspects of ETPs, and their transmission to the economy, are not being meaningfully captured in the forward-looking modelling frameworks currently used to evaluate the economic impacts of environmental change. The severity of physical climate- and nature-related financial risks are thus likely significantly underestimated at present, and mitigation action is not of the necessary scale.
- Policymakers should consider a wider range of modelling approaches that can better represent the economic impacts of crossing ETPs, such as accounting for the non-substitutability of critical ecosystems; indirect effects through (global) value chains; and the role of shorter-term, high-magnitude shocks. Priority approaches to explore include multi-regional input-output models and better parametrised damage functions.
- However, the fundamental uncertainty associated with ETPs requires policymakers to explore other approaches beyond risk quantification. A 'double materiality' perspective offers a promising way forward. There is a role for financial authorities to identify and map where financial institutions are exposed to economic activity that is driving ecosystems towards tipping points. These exposures are unlikely to present material enough transition risks to be adequately managed by individual financial institutions, but, given the magnitude, irreversibility and uncertainty associated with ETPs, they represent possible sources of systemic physical risk that require intervention at the macroprudential level.
- The scale of environmental breakdown posed by ETPs necessitates a precautionary approach. This must focus on rapidly eliminating negative drivers to prevent thresholds being crossed *ex ante*, rather than attempting to predict the timing and outcomes of complex Earth system changes. Ultimately, this approach will need to be led by governments, and requires central banks and financial supervisors to coordinate with policymakers in ministries of finance, industry and environment to fulfil their primary mandates of price and financial stability.

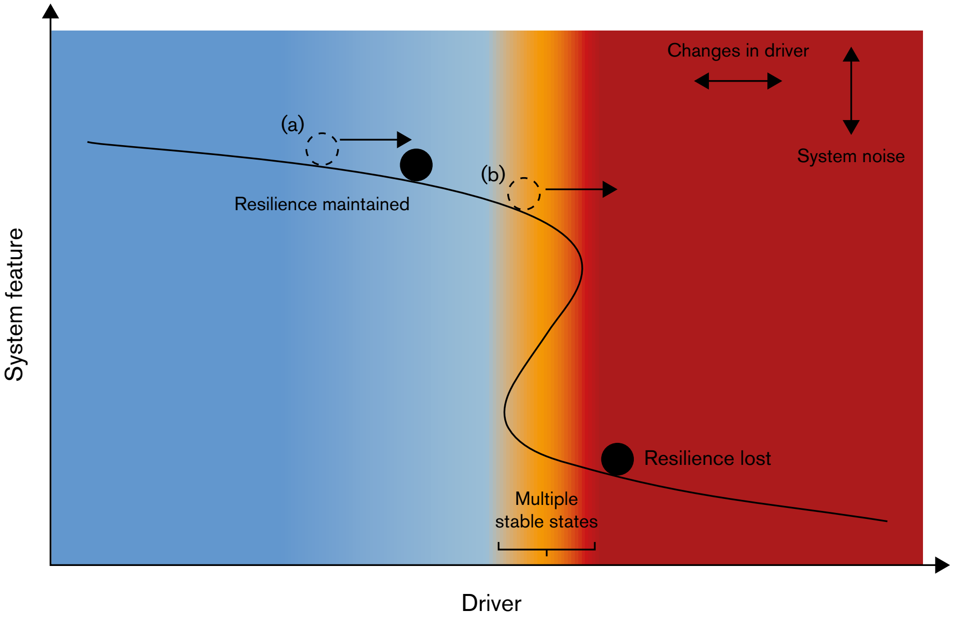
1. Understanding critical ecosystems as Earth system tipping points

There is an emerging scientific consensus that large-scale tipping points exist within all key spheres of the Earth system – the cryosphere (ice sheets), atmosphere and ocean circulations, and the biosphere (the living world).[1] A tipping point refers to a critical threshold, measured in terms of drivers external to the system, at which additional pressure causes a system to lose resilience and undergo self-propelling change into a qualitatively different state (Figure 1).[1] These 'Earth system tipping points' would have catastrophic societal and economic impacts if crossed.

Tipping points in the Earth system are characterised by:

- Non-linearity: a disproportionate relationship exists between drivers and change, which depends on the level of accumulated pressure over time.
- Self-propelling change: once a tipping point is crossed, change will continue even if pressures are eliminated from the system, due to strongly amplifying feedbacks.
- Irreversibility: changes will be very difficult, if not impossible, to reverse on timescales relevant to our ability to adapt and avoid the worst impacts of climate change and nature loss.
- Abruptness: for many tipping points, the change will be rapid relative to the drivers that cause it, with adverse implications for adaptation by socio-economic systems.

Figure 1. Tipping point dynamics in a system with two stable states



At (a), an increase in pressure from a driver (e.g. regional temperature) causes minimal change to the system feature (e.g. forest cover). Close to the tipping point at (b), non-linearity leads the same amount of pressure to cause the system to lose resilience and change state. Source: authors' illustration.

Critically, there is deep uncertainty regarding precisely when a tipping point may occur or what its impacts may be. Identifying the level of accumulated external pressures that could trigger a collapse to an alternative state is a monumental task for any given system. As well as these external pressures, which are somewhat deterministic (though still subject to hugely complex dynamics), parts of the Earth system contain environmental variability that is fundamentally random (known as 'noise' or stochastic variability) and therefore can never be precisely forecast.[2] Moreover, the new states that arise from crossing Earth system tipping points will be outside the realm of current human experience, with no historical precedent. These aspects confound the modelling of both thresholds and impacts.[1]

By raising temperatures, intensifying droughts and altering precipitation patterns worldwide,[3] climate change is a core driver in many parts of the Earth system that contain tipping points. For example, rising polar temperatures cause melting that could trigger the collapse of the

Greenland or Antarctic ice sheet if large-scale tipping points are crossed, leading to multi-metre sea level rises over the long-term.[1] Allowing global warming levels to breach 1.5°C or 2°C increases the likelihood of crossing multiple tipping points, driven by climate change, to high or very high respectively.[4] With current policy trajectories suggesting temperatures could reach 2.7°C above pre-industrial levels, climate-driven tipping points are moving from low-likelihood, high-impact events (or 'tail risks') to high-likelihood, high-impact events subject to high uncertainty.

However, natural systems are also under pressure from a more complex interplay of drivers that compound the effects of climate change, including land use change, overexploitation, pollution and invasive species.[5] These drivers are at risk of triggering tipping points in the biosphere but have largely received less attention than climate change.

Only around half of originally forested land area remains and this continues to decline at an alarming rate, far below the 75% required to maintain Earth system stability.[6] The introduction of harmful substances into natural systems, such as excessive levels of nutrient pollution, can interfere with ecosystem assemblages. Nutrient flows are currently double the rate determined as a safe planetary boundary by Earth system scientists.[7] While cryosphere and ocean tipping points are primarily driven by climate change, those in the biosphere face huge pressures from all other drivers of nature loss. These multiple drivers make thresholds even harder to predict and can bring forward the timeframe of abrupt collapse.[8]

While all tipping points pose globally systemic risks, those in the biosphere – ecosystem tipping points (ETPs) – require specific intervention. In addition to the presence of multiple drivers that make their behaviour particularly uncertain, ecosystems can collapse much faster than cryosphere and ocean sub-systems. Crossing ETPs will permanently alter key features of nature that underpin local, regional and global economic activity. Importantly, through the role of the biosphere in sequestering carbon, crossing ETPs would amplify climate change and compound its impacts, leading to further Earth system destabilisation. ETPs are therefore critical to understanding how nature-related risks could threaten economic stability.

In the remainder of this report, we examine key ETPs in more detail, outlining why they should be prioritised by financial and macroeconomic policymakers (section 2). Section 3 explores how ETPs could impact the economy and financial system to create risks, through regional effects, as well as through global feedbacks on climate change and value chains. Section 4 briefly reviews how current approaches – namely integrated assessment modelling – account for these dynamics when quantifying risks. We conclude by providing initial directions for further research and policy considerations.

2. Ecosystem tipping points requiring prioritisation by policymakers

While ETPs can occur at all ecological scales, a growing body of evidence has identified several critical ecosystems that could tip at large, potentially transboundary, scales[i]. These ETPs, presenting huge economic and macro-financial risks (section 3), warrant particular attention by policymakers. This section introduces these ETPs from the perspective of their possible states (what will the system transition to?); feedbacks (which reinforcing cycles support self-propelling change?); and the nature of their direct drivers (which pressures on nature – climate change, land use change, pollution, overexploitation and/or invasive species – are driving the system towards a tipping point and require intervention?).

The Amazon rainforest

Multiple lines of evidence suggest that loss in moisture cycling due to water stress will lead large parts of the Amazon rainforest to collapse into a degraded or non-forested state.[9] Self-amplifying feedback mechanisms between fire, tree cover and rainfall cycles exist at a range of scales, which allow the rainforest to generate much of its own rainfall, since intact forest cover supports moisture recycling to the atmosphere and supresses fires, which in turn supports forest stability[10] (Figure 2).

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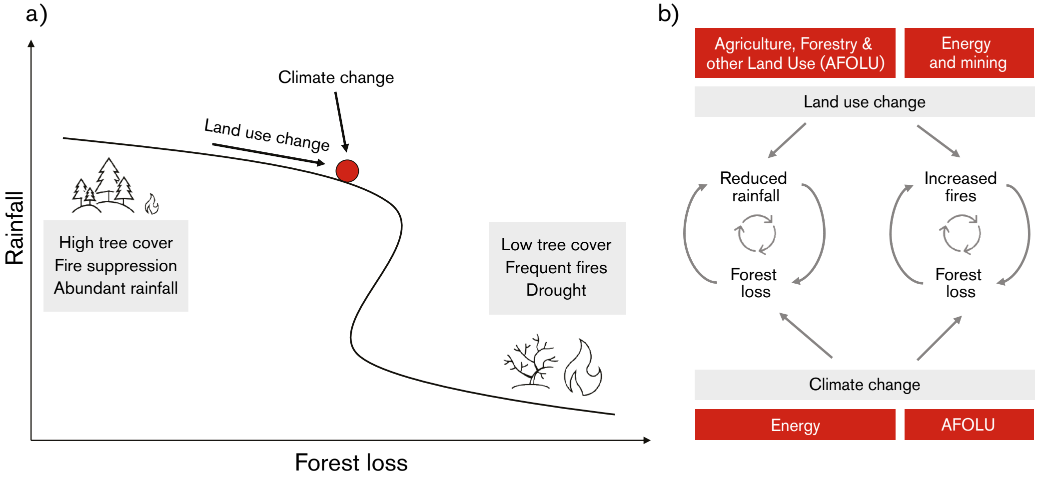
[i] The ecosystems we outline are not the only ones that may contain tipping points. However, they have been identified with at least medium confidence by the scientific community and are associated with regional to global impacts.[1]

Figure 2. Dynamics associated with an Amazon tipping point



a) Climate and land use change affect forest loss and rainfall, pushing parts of the Amazon towards a tipping point and a new ecological state. b) Climate change and land use change interfere with self-amplifying feedback loops. Climate change causes regional drying, which reduces rainfall and increases the frequency and severity of fires, which both cause tree cover loss. Lower tree cover then allows fires to spread more rapidly and decreases moisture cycling, which then causes more forest loss. Adapted from Lenton et al. (2023)[1] with key economic activities that cause land use change and climate change labelled. Source: authors' illustration

These feedbacks usually stabilise the forest, but, if disrupted, may lead to runaway change that would cause the system to 'tip' into a degraded forest, non-forested savannah or grassland across part or all of the Amazon Basin.[4,12,13] Once collapsed, positive feedbacks between fires and vegetation state – a lack of tree cover allows fires to spread more rapidly, which further reduces tree cover – will likely prevent the ecosystem from recovering to forest.[1]

Climate and land use change are the key pressures on the Amazon rainforest. Global warming is causing regional drying and more frequent droughts, interfering with the Amazon's forest-rainfall feedback at regional scales.[10] Land use change, through deforestation and forest degradation, directly reduces tree cover and moisture cycling (evapotranspiration), and also allows fires to spread more rapidly.[14] The Amazon rainforest is thought to store between 100-200 gigatonnes of carbon, large parts of which could be destabilised within the coming decades if pressures are not addressed.[9]

Tropical peatlands

Peatlands are wetland ecosystems with specific ecological conditions that store huge volumes of carbon as peat, which is partially decomposed organic matter. Waterlogged conditions, dense overlying vegetation and low oxygen levels prevent its decomposition.

The loss of tropical peatlands is characterised by non-linearities that can lead to rapid collapse and long-lasting changes in ecological functioning. Tropical peatland ecosystems, the largest of which are found in Southeast Asia, the Congo Basin and the Amazon, maintain their stability through amplifying feedbacks at a range of scales, in particular relating to high water levels.[15,16] Past a critical threshold, declining water levels will cause rapid and irreversible drying, decomposing peat, and cause subsidence that lowers the water level even further.[17] This triggers peat decomposition on levels many orders of magnitude greater than when intact and far beyond the original site of disturbance,[18,19] releasing carbon and reducing peatlands' natural resilience to fire. Peatland ecosystems then enter a qualitatively different regime characterised by more flammable overlying vegetation and more frequent, intense burning.[20]

Land use change (drainage, deforestation and conversion to monocultures) is the key pressure on tropical peatland stability. Drainage lowers water levels, while deforestation and monoculture conversion affect overlying and underlying vegetation dynamics.[21] Climate change is increasingly a key driver, in some regions, as drying and rainfall losses will occur across the tropics. This will impact water levels and could lead to peatland collapse. Such transitions are thought to have played a role in the long-term history of some tropical peatlands.[22,23] Once peatlands decompose, aspects of ecosystem functioning, such as carbon storage and plant diversity, take centuries to return, rendering losses irrecoverable on any meaningful policy-relevant timescale.[24,25] These tropical ecosystems store at least 100 gigatonnes of carbon worldwide, on a similar order to the Amazon rainforest.[26]

Boreal forests

Boreal forests, found in the Northern regions of Europe, Asia and North America, also have multiple stable states and may undergo abrupt changes in response to pressures.[27,28] These changes are driven by complex feedbacks between tree type, permafrost, fire and pests, with two potential tipping points in the north and the south of the forest respectively.[4] In the southern boreal forest, tipping could occur as rising local temperatures increase drying, and the risk of fire and bark beetle outbreaks, risking a self-reinforcing cycle of tree loss and associated carbon loss. Behaviour in the north is much less certain – rising temperatures could lead to abrupt forestation of previously unforested areas, with negative implications for biodiversity, as well as biophysical climate feedbacks that would add to global warming despite tree cover gain.[1]

Changes in local air temperature, caused by climate change, are the key driver[1,4], but land use change and invasive species, such as bark beetles, can also trigger amplifying feedback cycles.[27] Land use change, due to deforestation and forest degradation in the boreal zone, could lead to tipping points sooner than currently estimated.[4,8] Feedbacks exist between drivers, for example, climate change allows invasive species in the boreal region to spread more rapidly.

Coral reefs

Coral reefs are at risk of collapse to a non-coral state, driven primarily by climate change. However, pollution and overexploitation pose important secondary threats. Rising ocean temperatures and acidification due to ongoing greenhouse gas emissions are the key pressure on coral reef integrity.[29] However, other proximate stressors can weaken resilience. Excessive nutrient pollution (from agricultural runoff and sewage discharge) and overfishing both interfere with complex symbiotic processes, and can lead to exponential coral loss.[30,31] In some regions, these threats are more important than climate change.[1] Minimising these can help boost resilience, but must be a rapid intervention alongside deep greenhouse gas emissions mitigation, since 90% of global coral reefs may collapse at global warming of 1.5°C, which under current trajectories will be reached in the first half of the 2030s.[3]

Mangroves

Mangroves are forest ecosystems at risk of mass dieback to tidal flats in response to both climate change and land use change.[1,32] The feedbacks that cause self-amplifying change are not well understood. Linked to sea-levels, temperature, nutrient and sediment runoff, and habitat availability, they can combine to cause mangrove collapse.[33] More frequent and extreme weather events linked to climate change add to the long-term pressure of land use change and pollution, reduce mangrove resilience, and risk regional tipping events that prevent re-establishment.[1] While mangrove loss driven by land use change has declined in the past decade, they remain one of the most vulnerable ecosystems globally with concentrated hotspot areas of loss, such as in Indonesia, Australia and Myanmar, that require prioritisation.[34,35]

Threats to biodiversity

Abrupt and rapid shifts in these ecosystems' states will have major implications for species that are adapted to current ecosystem states, posing huge biodiversity risks. Each of these ecosystems hosts unique and rich biodiversity. Environmental breakdown will decrease ecosystem resilience, meaning they are less able to recover from shocks. The Amazon is home to a huge proportion of global tropical biodiversity, including 16,000 tree species and 18% of currently documented plants,[36] with much remaining undiscovered and undescribed. Tropical peatlands are vital for freshwater fish diversity[37] and mostly occur in biodiversity hotspots, such as the Amazon, Congo Basin and Borneo. Mangroves support both terrestrial and marine life, including important commercial species.[38] At least 25% of all marine species rely on coral reefs.[39] Shifts in vegetation state – rainforest to savannah, mangrove to tidal flat – will have major implications for species adapted to previous conditions and risk irrecoverable losses.[1] This biodiversity underpins various services provided by these ecosystems, such as pollination and carbon storage, and its loss increases the possibility of widespread societal impacts.[40,41]

Tipping point thresholds

The thresholds at which tipping could occur are highly uncertain due to the inherent complexities of ecosystems and the presence of multiple drivers. The scientific community has only limited knowledge of the important feedbacks that control ecosystem resilience,[18] leading to a huge range in the estimates for critical tipping thresholds. The Amazon has received the most attention from the scientific community, with thresholds for partial dieback ranging from 2 to 6°C global warming or 20 to 40% of original tree cover loss.[4,10,42] Estimates for boreal forests are between 2 to 7°C global warming.[4] Some drivers are already approaching the lower bounds of these estimates. Global average warming levels are already 1.2°C, while 15% of the Amazon is already deforested and another 17% is degraded.[9] Importantly, thresholds are usually estimated for each driver independently, neglecting the fact that multiple drivers are compounding, not additive, leading to a much earlier likelihood of collapse.[8]

In summary, a range of terrestrial ecosystems have the potential to tip into degraded states at large scales, under relatively short timeframes. Pinpointing the thresholds for tipping in terms of external drivers proves particularly challenging, since we do not know all the relevant feedbacks and multiple drivers add complexity. Nonetheless, some drivers of nature loss are nearing critical levels, potentially leading to irreversible changes in these ecosystems and their biodiversity.

3. Threats to financial and price stability from ecosystem tipping points

Functioning ecosystems form the basis of economic, and hence financial, stability.[43] Recent studies by the Network for Greening the Financial System (NGFS) have established that losses to biodiversity and ecosystem services from environmental degradation can affect the real economy through multiple channels, which in turn may impact the financial system through strategic, credit, market, underwriting, liquidity and operational forms of financial risk, which can further exacerbate economic risks.[44] Breaching ETPs will amplify the magnitude and pace of physical nature-related financial risks, challenging the common perception of physical risks as longer term and slower moving than transition risks. This section outlines how crossing ETPs will impact key ecosystem services and explores how this could transmit to the economic and financial system.

3.1 Loss of ecosystem services

Biodiversity and nature contribute to human wellbeing through ecosystem services, also termed ‘nature’s contributions to people’.[45] Ecosystem services can be both material and non-material.[40] They directly provide society with tangible goods, such as food and materials (provisioning services); mediate and maintain natural processes important to human wellbeing (regulating services); and provide opportunities for socio-cultural fulfilment (cultural services).[44,46] While the monetary and economic valuation of ecosystem services is both ethically and methodologically contested,[47] considering ecosystem services qualitatively provides a useful analytical framework for understanding the globally significant impacts that could arise from breaching ETPs.

Crossing ETPs will abruptly and permanently change the quantity and quality of the services that these ecosystems provide. The new ecosystem states that arise from ETPs will have fundamentally different ecological and hydrological characteristics that threaten the wide range of final services on which societies currently depend (Table 1). Existing pressures are already causing environmental degradation and resulting declines in these services, but crossing ETPs will increase rates of decline to far greater magnitudes than previously experienced.[48]

Importantly, the occurrence of ETPs is likely to sharply decrease the ability of economies to compensate and ‘substitute’ for losses in ecosystem services through technology or trade, therefore increasing vulnerability.[49] Decreased adaptive capacity will occur because ETPs are likely to result in *higher-magnitude* losses to *multiple* ecosystem services in *multiple* locations, with compounding effects.

Regulating and maintenance services

Regulating and maintenance services include the regulation of physical, chemical and biological conditions, such as water flows, fire protection, flood and storm protection, pest and disease control, and landscape stability.[50]

Water cycle changes arising from an Amazon tipping point will compromise its central role in the global regulation of water flows. The forest-rainfall feedback that drives tipping (section 2) is central to the abundant rainfall that characterises the Amazon basin.[10] Land use change has been projected to cause sharp, permanent decreases in rainfall and increasing droughts across the basin and further downwind. Amazon moisture cycling is a global ecosystem service that operates across continents. These ‘teleconnections’ mean that the negative impacts of an Amazon tipping point may extend to large parts of South America;[51] important farming zones in the United States’ Midwest;[52] and further afield, including the Tibetan Plateau and West Antarctic ice sheet.[53,54]

Resilient ecosystems regulate floods, mitigate the impacts of storms and stabilise landscapes. Mangroves and coral reefs serve as natural defences that dissipate energy, preventing erosion and reducing the impact of storm and wave surges in coastal regions.[55,56] Intact tropical peatlands reduce the risk of flooding by regulating water flows during rainy seasons and supporting landscape integrity, while collapsed peatlands result in rapid and irreversible land subsidence, potentially exposing parts of Indonesia and Malaysia to permanent and sustained flooding.[16] Forest cover in the Amazon moderates peak water flows, meaning that deforested areas experience aggravated flood impacts and increased soil erosion.[57] Vegetation changes from ETPs will drastically reduce – if not eliminate – these regulating services, increasing our vulnerability to extreme events. Pollination, pest and disease control will also be compromised through biodiversity losses.[58–60]

Crucially, ETPs will have substantial impacts on global climate regulation, determining the overall magnitude and severity of climate change, and increasing the level of climate-related hazards (such as regional heating, droughts, floods, storms). Many of the vegetation changes caused by ETPs – forest to grassland, mangrove to tidal flat, peat accumulation to decay – move ecosystems from high-carbon storage to lower-carbon storage states.[25] Tropical ecosystems with tipping points, such as the Amazon rainforest, tropical peatlands and mangroves, currently sequester globally significant volumes of carbon in the order of 220 gigatonnes. This is around 20 years of global CO2e emissions based on 2022 rates, that could be quickly destabilised by tipping events, on timescales of months to decades.[1,26,61] Emissions from fires, in particular, can occur very rapidly – the 2015 peatland fires in Indonesia released enough carbon to exceed the annual emissions of the US economy in just five months.[62]

The potential carbon lost from ETPs will be irrecoverable on timescales relevant for avoiding the worst impacts of global warming, making these ecosystems essential for climate protection.[25] Importantly, crossing ETPs could trigger climate-driven tipping points in other areas, including outside of the biosphere.[54,63] This loss in climate regulation is not consistently included in the Earth system models that are used for future climate change projections, meaning ETPs could lead to climate impacts occurring much sooner than currently predicted.[1,64]

Provisioning services

The natural ecosystems highlighted in this report are important sources of provisioning services – the tangible benefits provided to society such as food, water, and genetic resources - in their current form. The Amazon rainforest, boreal forests, and tropical peat swamp forests are central sources of timber, as well as non-timber forest products (NTFPs) such as rubber, Brazil nuts, and berries.[65–67] Mangroves also provide timber, as well as sources of food and fisheries.[38] Coral reefs directly supply up to a quarter of the fish catch in some regions.[68,69] The Amazon and tropical peatlands are important sources of water provision for the surrounding areas.[58,70] Ecological changes arising from ETPs will compromise the supporting habitats required for this provision.

Cultural services and intrinsic value

Finally, these ecosystems are also of immense cultural value, both to humans and intrinsically. The transboundary systems we highlight are some of the world's most iconic environments, providing important sites for recreation and tourism, as well as directly facilitating the livelihoods and knowledge systems of local communities. Beyond the value they provide to humans, they have intrinsic value and merit conservation in their own right.

3.2 Economic impacts

Economic risks arise from ETPs since losses to ecosystem services can affect production, capital stocks, labour and household welfare at local, regional or global scales. These impacts can be chronic (e.g. declines in pollinator abundance and diversity gradually resulting in reduced crop yields) and/or acute (e.g. loss of disease control that leads to a pandemic). Impacts arise from first-order effects, where households and businesses are directly dependent on nature; and from second-order effects, for actors indirectly exposed through value chains.[44]

Overall risks are a function of three factors: hazard (a natural or human-induced physical event), exposure (the extent to which socio-economic systems could be affected by this hazard) and vulnerability (the extent to which socio-economic systems can adapt to or withstand the hazard).[71,72] Losses to ecosystem services from ETPs can impact both the level of hazard and increase vulnerabilities.

First-order effects

A wide range of business sectors are directly exposed to the ecosystem services at risk from ETPs (Table 1). Particularly high economic impacts could arise from the losses to maintenance and regulating services described above. For example, the agriculture sector, which is particularly exposed to tropical peatlands and the Amazon, depends heavily on water flow maintenance services, the regulation of extreme events such as fires and floods, and pollination to maintain yields. Sharp declines in rainfall within and beyond the Amazon basin are projected to produce double-digit yield losses of key crops in South America,[58] leading to reduced output and lower agricultural revenues.[73] Energy generation can also be highly dependent on water flow maintenance services. It is placed at huge risk from Amazon tipping, as hydropower provides over half of final energy consumption in Amazon countries such as Brazil, Colombia and Peru.[74–76] Reductions in rainfall due to Amazon forest loss could lead to hydroelectric energy capacity losses of up to 75% in Amazon countries, as well as further afield.[77] Long-haul transport, such as shipping, also relies on functioning water flows. Large-scale Amazon forest loss could heavily impact important routes, such as the Panama Canal, which facilitates US $270 billion worth of global shipping traffic and is already under strain from recent droughts.[78,79]

Table 1. How ETPs could generate physical risks through losses to ecosystem services and the economic activities implicated in direct drivers of tipping point dynamics

ETP	Key ecosystem services at risk	Economic impacts and sectors implicated	Direct drivers and main economic sectors implicated[ii]
Amazon dieback	▪ Decline in global climate regulation (diminished carbon sequestration abilities) ▪ Decline in regional climate regulation (reductions in rainfall, increased local temperatures) ▪ Reduced flood and storm protection ▪ Reduced soil erosion control ▪ Pollinator decline ▪ Diminished disease and pest control ▪ Loss in provisioning (timber, NTFPs, genetic material) ▪ Lack of opportunities for recreation and tourism	▪ Agriculture of all types (production losses, physical damages, asset value declines) ▪ Power generation, hydro (production losses, asset value declines) ▪ Long-haul transport (productivity losses) ▪ Households (health impacts, labour productivity declines, asset value declines, relocation costs) Value chain effects (as above, plus supply chain disruptions, increased costs of inputs).	Land use change: ▪ Beef ▪ Soy ▪ Forestry (timber, rubber) ▪ Oil and gas ▪ Mining ▪ Hydropower ▪ Palm oil Climate change: ▪ Carbon-intensive sectors, such as energy, materials, utilities and industrials

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[ii] See appendix for the literature used to identify drivers and implicated sectors.

ETP	Key ecosystem services at risk	Economic impacts and sectors implicated	Direct drivers and main economic sectors implicated[ii]
Boreal forest transitions	▪ Loss in provisioning (timber, NTFPs) ▪ Decline in global climate regulation (complex carbon and albedo effects) ▪ Decline in regional climate regulation (increased local temperatures) ▪ Diminished pest control	▪ Forestry (production losses, property value declines) ▪ Households (health impacts, labour productivity declines, direct damages, relocation costs) Value chain effects (as above, plus supply chain disruptions, increased costs of inputs)	Land use change: ▪ Forestry (timber) ▪ Oil and gas ▪ Mining ▪ Hydropower Climate change: ▪ Carbon-intensive sectors
Coral reef die-off	▪ Loss in provisioning (fisheries, genetic material) ▪ Reduced flood and storm protection ▪ Loss of mass stabilisation and erosion control ▪ Lack of opportunities for recreation and tourism	▪ Fisheries (production losses) ▪ Tourism (demand shocks) ▪ Real estate (physical damages, asset value declines) ▪ Infrastructure (physical damages, asset value declines) ▪ Households (asset value declines, relocation costs) Value chain effects (as above, plus supply chain disruptions, increased costs of inputs)	Climate change: ▪ Carbon-intensive sectors Overexploitation: ▪ Fisheries Pollution: ▪ Agriculture ▪ Aquaculture ▪ Oil and gas ▪ Real estate and infrastructure
Mangrove dieback	▪ Decline in global climate regulation (diminished carbon sequestration abilities) ▪ Loss in provisioning (timber, fisheries) ▪ Reduced flood and storm protection ▪ Mass stabilisation and erosion control ▪ Lack of opportunities for recreation and tourism	▪ Fisheries (production losses) ▪ Real estate (physical damages, asset value declines) ▪ Infrastructure (physical damages, asset value declines) Value chain effects (as above, plus supply chain disruptions, increased costs of inputs)	Land use change: ▪ Aquaculture (shrimp) ▪ Agriculture (rice, oil palm) ▪ Real estate and infrastructure Climate change: ▪ Carbon-intensive sectors
Tropical peatland collapse	▪ Decline in global climate regulation (diminished carbon sequestration abilities) ▪ Loss in provisioning (water, fisheries, food) ▪ Reduced flood and storm protection ▪ Reduced mass stabilisation and erosion control ▪ Loss of fire prevention ▪ Disease and pest control	▪ Agriculture (production losses, physical damages, asset value declines) ▪ Households (health impacts, labour productivity declines, lost livelihoods) ▪ Infrastructure (physical damages, asset value declines) Value chain effects (as above, plus supply chain disruptions, increased cost of inputs)	Land use change: ▪ Agriculture (oil palm, pulpwood) ▪ Forestry (timber, rubber) ▪ Oil and gas ▪ Mining Climate change: ▪ Carbon-intensive sectors

Extreme events such as fires, floods and storms can directly damage capital assets such as residential and commercial property, infrastructure and croplands, increasing costs or leading to relocation needs. For example, coral reefs and mangroves currently protect at least US $400 billion worth of built assets from extreme storms, with damages expected to double should they be lost.[55,56] Longer-term declines in mass stabilisation, soil erosion and fire suppression can erode the economic viability of entire geographical areas. For example, the subsidence caused by rapid degradation of tropical peatlands is expected to undermine the viability of agriculture in parts of Indonesian and Malaysian Borneo,[70] potentially leading to declines in land values and other assets.[80]

Beyond businesses, households will be significantly affected by loss of ecosystem services due to ETPs. Hundreds of millions of people depend directly on critical ecosystems for their food and livelihoods, and for protection from heat stress, fires, floods and pollution. For example, large-scale Amazon forest loss could expose over 10 million people to extreme heat stress risk.[81] These effects will impact labour productivity, household consumption and increase public health costs. They could also give rise to mass migration.

There are local studies that aim to evaluate these direct impacts of severe ecosystem service losses. For example, the 2015 Indonesian peat fires, which occurred over the space of just five months, cost Indonesia at least US $16.1 billion in short-term health costs and economic disruption. Lapola et al. (2018) assessed the socioeconomic damages of an Amazon dieback over 30 years as US $1-3.6 trillion based on 2018 net present value.[58] While still substantial compared to Brazilian Amazon GDP (an annual loss of 13%), these damages are certainly underestimates, not least because second-order and macroeconomic feedback effects are not considered.

Second-order and macroeconomic effects

While primary producers and households are directly affected by their dependence on nature, indirect and macroeconomic effects can also arise via value chains. Supply chain instability can arise for other actors that rely on primary producers for their inputs, such as industrial sectors and households in the case of hydropower,[82] or aquaculture and livestock, who rely on soy production for feed.[83] Supply shocks to agricultural or energy production can therefore have cascading impacts, including worldwide due to globalised supply chains. For example, concurrent droughts in China, Russia and Ukraine in 2010 led to major production losses in these three wheat-producing countries, pushed up food prices globally and compromised food security in several regions, with acute socio-economic impacts.[84] Given that ETPs would impair agricultural productivity in key food-producing regions such as South America and Southeast Asia, regional impacts could rapidly spread globally. There is rising concern over the possibility of global production instability in the food system if agricultural losses in major food-producing areas are synchronised, which is increasingly likely under projected global warming levels.[72,85]

Rising prices in agricultural commodities, as well as electricity and water, due to output losses from ETPs can lead to general inflationary pressures at national and global levels as these sectors are systemically significant for price stability.[86] For example, the 2021 drought episode in Brazil led to high inflation nationally, driven by food and electricity price rise.[87] The global value chains discussed above mean that inflation is not necessarily restricted to primary producing countries subject to the most acute supply shocks.[88] Concentrated market power in certain sectors can also amplify initial impacts on prices. This was demonstrated in the aftermath of the Ukraine-Russia war when grain and oil price rises were transmitted to other sectors by firms increasing markups and thereby profit margins – so called ‘sellers’ inflation’ – in a coordinated manner under the guise of supply shocks.[89] Moreover, impacts on global warming from crossing ETPs will also exacerbate climate-induced inflationary pressures, which can already be observed in high-income countries even before trade effects are taken into account.[90]

While shocks like this are already occurring on smaller scales, the economic risks from ETPs could be much more serious, since large-scale nature degradation limits substitution and adaptation possibilities, increasing vulnerability.[44] Losses to multiple ecosystem services are very likely to be compounding, rather than additive, as demonstrated in cases where shocks to climate regulation and disease control combine.[91] ETPs are key uncertainties in the overall trajectory of climate change, with, as mentioned, around 220 gigatonnes of carbon in tropical systems that could be destabilised under relatively short timeframes. The resulting feedback on global warming would amplify the impacts that climate change already poses to food systems, water security, health and livelihoods.[92] This means that as well as increasing *vulnerability*, crossing ETPs amplifies the severity of *hazards* facing economies.

Overall, breaching ETPs increases the possibility that physical risks could become material *systemically*, i.e. affecting multiple economies or regions in multiple compounding ways.

3.3 Financial risks

Transmission to traditional forms of financial risk

The microeconomic impacts of nature loss on businesses and households can impair their financial position, reducing profitability and the ability to service debts, as well as impacting the value of assets and collateral.[44] This can in turn lead to sources of credit, market and underwriting risks for financial actors who are exposed to these directly through their lending, insurance, investment and advisory activities (ibid).

Table 2 illustrates potential direct transmission channels between regional ecosystem service losses from ETPs to financial actors. Widespread credit, market and/or underwriting risks can make it more difficult for financial institutions to obtain refinancing or meet cashflow requirements in the short term, leading to liquidity risks.[93] The drastic magnitude of nature degradation will limit both short- and long-term substitution possibilities. A lack of adaptation options leads to more widespread and severe financial risks.

Table 2. Examples of how the impacts of ETPs could transmit into traditional categories of financial risk

Amazon dieback	**Credit risk:** Loss of rainfall and reduced river discharge following tipping of part of the Amazon reduces hydropower output across South America beyond Amazon countries, impacting hydropower revenues.[94] This reduces the profitability of hydropower producers since this level of physical risk may not be factored into business models, reducing their ability to manage debts.[95] Production disruptions could cascade to industry and households since hydropower provides the majority of electricity in the region.[74–76] This can sharply increase costs for industrial sectors,[82] increasing credit risks if adaptation possibilities are overwhelmed.[96] **Market risk:** Season-wide crop failures could impact companies' financial position and their market value depending on their position in the agricultural supply chain.[97] **Underwriting risk:** More severe droughts lead to production losses and increasing insurance claims by agricultural producers, leading to larger than expected insured losses.[98]
Boreal forest transitions	**Credit risk:** More frequent and intense wildfires can negatively impact property values,[99] reducing collateral values and increasing credit risks. Drops in affordable insurance cover may increase uninsured costs for households, impeding their ability to repay debts and increasing credit risks. **Market risk:** Permanent supply disruptions could lead to revenue declines and reduced profitability for timber companies, leading to lower market values, as well as increasing market volatility in sectors dependent on the timber supply chain. **Underwriting risk:** More frequent and intense wildfires across the boreal could damage properties, infrastructure and land on a large scale, leading to increased insured losses and straining reinsurance capacity, as is already occurring in Canada.[100]

Coral reef die-off	**Credit risk:** Declines in property values in coastal regions dependent on tourism may lead to decrease collateral values for loans secured by real estate, increasing credit risks. **Market risk:** A crash in fish stocks dependent on coral reefs could collapse fishing revenues, risking the market value of publicly listed fishing companies and increasing market risks.[101] **Underwriting risk:** Without reefs, annual capital damaged (property, infrastructure) by floods could double,[55] increasing insurance claims beyond expected levels.
Mangrove dieback	**Credit risk:** Greater storm impacts from mangrove loss could lead to increased costs for households to mitigate damages, potentially compromising the ability to service debt and increasing credit risk. **Underwriting risk:** Greater storm impacts than expected from mangrove loss could lead to property losses rising by US$270 billion for one-in-a-hundred-years events,[56] increasing insurance claims beyond expected levels.
Tropical peatlands collapse	**Credit risk:** More frequent flooding leads to crop production losses, impacting revenues and reducing the ability of companies to repay debt. Subsidence and low yields lead to declines in the value of agricultural land and production assets on which lending is often secured,[102] impacting collateral values and increasing credit risk. **Market risk:** Acute fires and flooding in a key agricultural region such as Indonesia could lead to a sharp decline in the market values of securities linked to the government or to key commodity producers. **Underwriting risk:** More frequent and intense fires than expected cause increases in insurance claims by agricultural producers and health insurance claims, increasing insured losses.

Broader macroeconomic deterioration, such as impacts on inflation and investment, due to large-scale nature loss can in turn weaken the balance sheets of financial institutions.[44] For example, inflationary pressures may necessitate a monetary policy response that could reduce the ability of certain economies to invest in adaptation and transition policies, further increasing their vulnerability to nature and climate shocks, and thus heightening financial risks.

Current financial sector exposures to losses in ecosystem services

Numerous static case studies, aiming to evaluate dependencies on nature by sector, demonstrate that financial sector exposure to losses in ecosystem services could be substantial and extend beyond the more heavily regulated banking sector. Van Toor et al. (2020) found that 36% of the non-financial portfolios of Dutch financial institutions (banks as of 2017; pension funds and insurance companies as of 2019) was comprised of companies that are highly or very highly dependent on one or more ecosystem services.[93] Similar results were found for France[47], and also Brazilian and Malaysian banks, where between 40 and 54% of non-financial portfolios were highly or very highly dependent on one or more ecosystem service.[103,104] In Europe, some 75% of corporate loan exposures as of the end of 2021 had a high direct dependency on at least one ecosystem service.[105]

Once indirect exposures were considered, *all* non-financial exposures of French financial institutions were at least partly dependent on ecosystem services at the end of 2021, illustrating the materiality of cascading exposures through value chains.[47] Some of the highest dependencies were on climate regulation, water provision, and flood and storm protection – to which ETPs pose some of the most severe future losses.

The substantial exposures identified by these studies suggest that sharp declines in ecosystem services, especially across multiple types, as posed by ETPs, could result in significant financial losses.

Systemic risk: financial interconnections and feedbacks

We have already explored how risks from ETPs can spread through globalised value chains. However, the financial system itself is also highly interconnected and prone to amplifying initial shocks through internal feedbacks or 'contagion' effects. Second-order exposures, for example to other financial institutions holding assets subject to physical and transition risks, can amplify initially small shocks. These second-round effects can be comparable in magnitude to, or in some cases larger than, first-round effects, as demonstrated for climate-related risks.[106,107]

Feedback effects also exist between the macroeconomy and the financial system. For example, excessive speculation on commodity derivatives – financial products linked to food prices – can amplify food price volatility and becomes more prevalent during inflationary episodes.[108] This has become a more common part of financial business practices, with speculative activity increasing since 2020 (ibid). Interconnectedness between banks and commodity trading firms through such derivatives could add to overall financial stress in times of volatility, especially if the same banks are also directly exposed to commodity traders through funding and investment activities.[109]

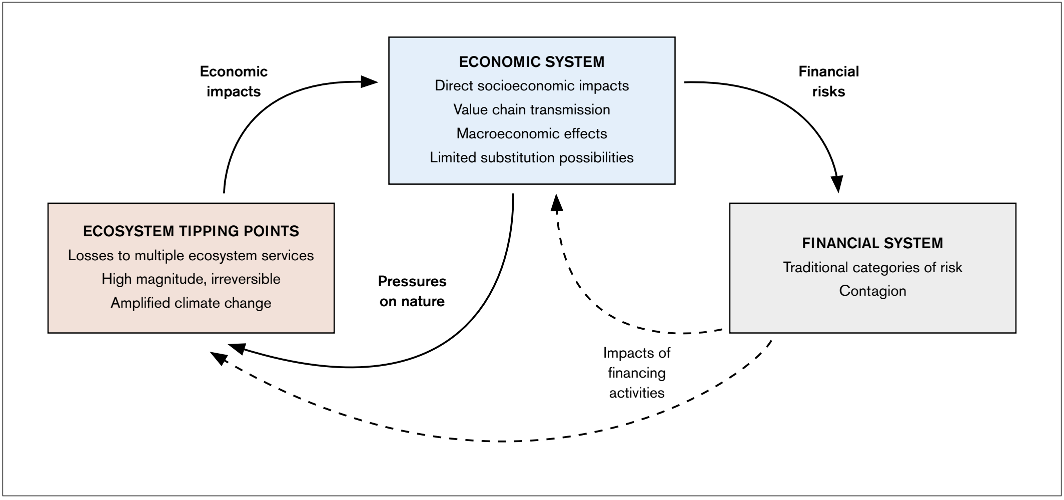
Endogenous risk: financial sector impacts on nature and double materiality

Financial actors may indirectly contribute to the risks posed by ETPs through capital allocation decisions linked to activities driving nature loss – termed 'double materiality' (Figure 3).[110,111] A concentrated group of economic sectors are linked to the direct drivers of ETPs, such as land use change (Table 1), and therefore play a role in increasing physical risks.

Although detailed research on financial flows linked to the degradation of specific critical ecosystems is limited, it is clear that a wide range of financial actors facilitate the overall activities of companies in these sectors. One study found that several asset managers hold significant equity positions in companies implicated in Amazon and boreal forest tipping dynamics.[112] Moreover, between 2016 and 2023, financial actors facilitated over US $300 billion in financing (across lending and capital markets activities) attributable to 'forest-risk commodity sectors' – soy, beef, palm oil, timber, pulpwood and rubber production – that are important for a range of ETPs[113] (Table 1). In some cases, financial actors are directly exposed through acquisitions of agricultural land as a portfolio asset,[114] a practice that has been linked to elevated levels of land use change and biodiversity losses.[115]

Such exposures should be identified as transition risks by financial institutions, given that negative impacts in critical ecosystems are increasingly subject to both regulatory and civil society scrutiny. Yet most financial actors score very poorly on assessments of their environmental risk management policies for these sectors, suggesting that services are currently being provided without the proper safeguards.[113] This suggests that these activities are not currently being managed as *material* sources of transition risks by individual financial institutions. This is likely due to exposures to key economic sectors implicated in tipping dynamics, such as agriculture and forestry, being small proportions of many financial portfolios. However, by enabling these activities, financial actors could exacerbate the substantial physical risks from ETPs to which they, or other parts of the system, are exposed.

Figure 3. Potential macro-financial dynamics associated with crossing ETPs



Losses to multiple ecosystem services in a high-magnitude way will cause substantial economic and financial risks. The financial system may play a role in amplifying risk through feedback effects, and by enabling economic activities linked to ETP drivers in specific ecosystems ('double materiality').
Source: authors' illustration

In summary, crossing ETPs will lead to collapses in ecosystem provisioning, regulating and cultural services that will cause huge negative impacts for the sectors and societies that depend on them. Risks can quickly spread through value chains and to the macroeconomy, leading to financial and price stability issues in geographies quite distant from the affected ecosystems. Systemic risks may arise as ETPs cause losses to multiple ecosystem services in ways that are difficult, if not impossible, to substitute and will compound the effects of global warming. The financial system is likely to play a role in amplifying overall risks, including by failing to individually manage exposures to economic activities that pressure specific ecosystems towards tipping points (Figure 3). In the next section, we explore the extent to which current efforts to quantify climate- and nature-related risks adequately account for these dynamics.

4. Quantifying the risks of ecosystem tipping points

Scenario analysis approaches are being developed to assess what the potential magnitude of financial losses from environment-related risks could be. Given the lack of historical data and uncertain nature of the risks posed by climate change and nature loss, these modelling exercises are forward-looking, and dynamically assess potential macroeconomic and financial impacts that could arise under certain pathways.

However, tipping points are rarely included in the integrated assessment models (IAMs) predominantly used for forward-looking scenario analysis.[116] For example, the suite of climate scenarios developed by the NGFS and widely used in the financial services industry does not include tipping points when estimating the economic impacts of physical climate risks.[117] Where they are included, the dynamics we outline in sections 2, 3 and 4 are not represented adequately, as we outline in this section.

Initial efforts have been made to simulate the macroeconomic consequences of crossing tipping points from both climate and nature perspectives. A first approach – used in stylised 'cost-benefit' IAMs – aims to integrate tipping points into damage functions, which are econometric parametrisations that link changes in climate variables (e.g. temperature, sea-level rise) directly onto macroeconomic variables (e.g. GDP, consumption).[118] A second approach – used in more complex 'process-based' IAMs – aims to map physical dependencies (transmission channels) between specific sectors (e.g. agriculture) and ecosystem services (e.g. pollination). Tipping points can then be stylised as shocks to the provision of certain ecosystem services, integrating cumulative impacts across various transmission channels, to estimate the overall macroeconomic impact of a collapse.[119, iii]

Tipping points are currently represented simplistically in the damage functions used in cost-benefit climate IAMs to estimate chronic physical risks in ways that are not in line with scientific evidence. Methodological choices in how damage functions are parametrised can mute quantified economic impacts by at least an order of magnitude.[120] For example, many damage functions include only a limited number of tipping points, if any, that occur

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[iii] There are also more general criticisms of climate/nature IAMs, beyond their representation of tipping points, but these are beyond the scope of this policy brief. See refs 119, 121 for fuller discussions of environmental (e.g. role of equilibrium climate sensitivity) and economic (e.g. discount rate, equilibrium assumptions, substitutability, treatment of the financial sector) criticism of climate, and nature-related, integrated assessment modelling, respectively.

as low-probability, high-impact events in isolation from each other (i.e. only occurring at high global warming levels and not considering the role of non-climate drivers). This contrasts with the latest evidence that tipping points are increasingly likely at global warming levels above 1.5°C and may interact with each other or trigger tipping cascades.[4,63] Furthermore, researchers often parametrise climate damage functions as quadratics, when evidence suggests that exponential or logistic functions would better reflect the rapidly accelerating *rates* of physical impacts under tipping point scenarios.[118,121] Focusing on a reduced number of climate variables impacted by ETPs and poor treatment of non-market impacts (e.g. ecosystem services, health) also leads studies to consistently underplay possible damages.[48]

These methodological choices in cost-benefit IAMs lead to perverse findings that do not reflect the catastrophic socio-economic damages that would occur if multiple tipping points were crossed. For example, Dietz et al. (2021) integrate the impact on climate regulation and sea-level rise of eight tipping points, finding the social cost of carbon increases by a median of just 25% (with the Amazon dieback contributing just 0.1%), with very modest impacts on global consumption.[122] The authors acknowledge that these findings are certainly underestimates, arising from not considering impacts on other climate variables or ecosystem services, as well modelling damages as a smooth quadratic.[123,124]

Damage functions can be improved to better account for the dynamics associated with tipping points. Cai et al. (2015) address some of these weaknesses in a modified climate damage function that requires limited substitutability of ecosystem services, abrupt and irreversible change, and random ‘noise’ in climate variability.[118] Including these aspects for just one stylised tipping point increases the social cost of carbon (SCC) – the standard metric used by economists to estimate the welfare impact of climate change – by between 60–300%. For multiple tipping points that interact, the SCC increases by 800%.[120] This underscores the importance of adapting parametrisations used to reflect scientifically robust tipping dynamics, if they are to be used to inform mitigation action.

The few studies using process-based IAMs that incorporate ecosystem services [iv] to estimate physical risks of nature loss also underestimate

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[iv] For example, an IAM used to evaluate nature-related physical risk using this approach is GTAP-InVEST.[125] Prodani et al. (2023) apply a stylised shock to certain sectors based on their pollination dependency in a purely economic model, MAGNET (The Netherlands Environmental Assessment Agency (PBL) and Wageningen University), in order to simulate a tipping point in pollination services.[126]

the impacts posed by ETPs, by oversimplifying ecological and economic dynamics and their interconnections. Key regulating and maintenance services, such as flood and storm protection, are often overlooked in nature-economy models.[119] Where ecosystem services are included, some direct economic dependencies on them may still be missing (e.g. modelling the dependence of agriculture, but not hydropower, on water flow maintenance services) (ibid). Models also allow ecosystem services to readily substitute for each other or for other production inputs, which has the effect of 'smoothing' the magnitude of economic impacts (ibid), despite scientific evidence that many of nature's contributions to people are irreplaceable, especially at the levels of breakdown posed by ETPs.[43]

For example, Johnson et al. (2021) simulate nature-related tipping points by modelling the economic effects of the collapse of three ecosystem services (wild pollinators, fisheries and timber provision) and find that global GDP would reduce by just 2.3% annually by 2030, relative to no tipping points being surpassed[125] – outcomes which undermine the Earth system sciences consensus that crossing multiple tipping points would be catastrophic.[121] These mild overall results are explained by substitutability between losses in services being permitted in the model (e.g. it is assumed that technology may to a certain extent replace wild pollinators worldwide), which is highly unrealistic for global food supply. In addition, Johnson et al. (2021) do not model interactions between ecosystem services, despite the ecological evidence that these interconnections are vital.

Prodani et al. (2023) also model the macro-financial effects of a 100% loss in pollination services worldwide, finding only mild effects on global GDP and consumer prices.[v] [126] This arises in part due to substitution possibilities, for example between regions of agricultural production (e.g. replacing Brazilian production with Netherlands production, which leads to a net increase in Netherlands GDP under this scenario) and between agricultural inputs (e.g. replacing pollination with fertiliser). This is problematic since fertilisers and pollinators fulfil different functions in crop production, while such extensive geographical substitution is highly unlikely, particularly in the short term, which is likely to be the most relevant from a financial stability perspective.[126]

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[v] The Netherlands experiences a 0.4% rise in total consumer prices, despite a spike of 38% in agricultural crop prices, while Brazil, a key pollination-dependent commodity producer and consumer, experiences just a 3.6% rise in total consumer prices.

Ultimately, these assumptions mean that the impact on GDP from current models remains similar to the share in value added of sectors that are directly impacted; this leads to mild final impacts given that agriculture, one of the most exposed sectors, accounts for ~4% of global GDP.[119] While accounting for second-order effects through value chains would somewhat increase the final impacts, this still fails to account for food provision as an *essential* good required for any economic activity to occur. A scenario where ~2% GDP is lost due to agricultural losses (i.e. global agricultural output reduced by 50%) would not just impact sectors using agricultural output, such as food processing and distribution, but would lead to mass global food insecurity, forced migration and potential civil unrest, with correspondingly huge economic impacts that are challenging to incorporate into any model.

The outcomes from IAMs are important for understanding financial risks since they are used to develop standardised scenarios to test the resilience of the financial system to pathways of climate change and nature loss, and calibrate (macro)prudential responses. For example, Calice et al. (2021) explore how the macroeconomic conditions produced in response to the collapse of three ecosystem services[125] could impact the Brazilian banking portfolio, projecting a cumulative increase of 9% in nonperforming loans (NPLs) by 2030.[102] While significant, this is a highly conservative estimate, given that the services considered are not the most material to the Brazilian banking portfolio. Furthermore, most IAMs do not include an explicit representation of the financial sector and thus do not account for financial dynamics that could amplify the economic and/or financial impact of shocks (section 3.3).[119]

Taken together, these issues with IAMs mean that, at present, the economic and financial impacts of ETPs – as compounding losses to multiple ecosystem services with limited substitution possibilities – are not well understood. Understanding the biophysical aspects of ETPs, as well as their economic linkages, is enormously challenging. However, by simplifying biophysical and economic complexity, IAMs have a recurring bias towards underestimation that renders them unsuitable for decision-making and risk management. In the next section we discuss some first steps as to how these quantitative assessments could be improved and, given the fundamental uncertainty associated with ETPs, identify alternative approaches.

5. Policy and research considerations

ETPs should be of serious concern to macroeconomic and financial policymakers, including central banks, financial supervisors and ministries of finance, due to the potentially systemic economic and financial risks they pose. Central banks and financial supervisors have recently recognised that environmental risks could materially impact price and financial stability, aligning with their primary mandates.[127] Since crossing ETPs will amplify the magnitude of all climate- and nature-related risks, these ecosystems are crucial for financial policymakers to consider as part of any 'ecosystem-based' approach to risk prioritisation.[44]

Existing efforts by financial policymakers and the private sector in relation to nature loss have focused on risk assessment and disclosure, including exploring through static (portfolio-based risk assessments) and dynamic (forward-looking scenario analysis) approaches that aim to quantify the risks posed to financial institutions from environmental degradation.[127,128] These efforts rest on the understanding that increased information on the economic and financial risks of climate change and nature loss will be incorporated into market prices and thus managed within financial markets without additional intervention.[110]

As shown in this report, the dynamics of ETPs present specific challenges to this approach. The emergence of risks from ETPs will be abrupt, non-linear and historically unprecedented, making them difficult to meaningfully quantify. So far, these dynamics are not well captured by models that aim to link environmental changes to the macro-financial system. Economic damages and financial risks associated with crossing tipping points are severely underestimated, as studies simplify ecological complexity; miss key dependencies on nature; and do not adequately account for how shocks can be amplified through migration and health, value chains and the financial system. This bias towards underestimation means that, even if the identified risks were priced in, it would lead to mitigation action that is not of the necessary scale.

To address these challenges, we propose three main avenues for financial policymakers seeking to manage the potentially systemic risks of crossing ETPs:

- Embrace a wider array of static and dynamic approaches that can better account for the biophysical characteristics of ETPs and their connections with the macro-financial system, to improve quantitative understandings of economic and financial risks.
- Explore tools beyond risk quantification, given the irresolvable uncertainties associated with tipping dynamics, such as identifying and managing where the financial sector is exposed to negative drivers of ETPs and contributing to the build-up of system-wide physical risks (or 'double materiality').
- Coordinate with other ministries, such as those responsible for fiscal, environmental and industrial policy, and across jurisdictions, recognising that the current monetary and prudential policy toolkit will be insufficient to manage ETPs in a precautionary manner and prevent financial and price stability risks.

Alternative modelling approaches, both static and dynamic, can better incorporate the complexities of biophysical systems and their interaction with economies and the financial system, including non-linearities, cascading effects and non-substitutable losses. Input-output models or production network models, for example, could be used to trace the propagation of hazards through primary and subsidiary sectors in the short to medium term (NGFS 2023c).[119] Such models have already been used to examine the cascading transition risks arising from climate change due to stranded assets.[129,130] Because these models are static, they do not allow for substitution effects and may begin to better approximate the short-term impacts that could occur through ETPs. This contrasts with current dynamic IAMs that assume near-perfect substitutability. Damage functions used in cost-benefit climate- or nature-related IAMs can also be amended to much better incorporate tipping dynamics (section 4). Sector-based portfolio risk analyses, which currently lack an ecosystem-specific dimension, could be supplemented with national-level datasets on ecosystem functioning to better account for proximity to biophysical thresholds.[119] Pursuing these avenues will be a first step towards quantification efforts that are more representative of the potentially catastrophic risks posed by ETPs.

However, other challenges with quantitative approaches may prove insurmountable: for instance, the difficulties in modelling interactions between multiple tipping points and socioeconomic effects like migration.

The risks posed by ETPs and, by extension, nature-related risks more generally are ‘fundamentally uncertain’, rendering it impossible to accurately determine their overall magnitude with any certainty.[131] Forward-looking modelling and scenario-based exercises can be best seen, then, as a means to explore risks rather than manage them.

Considering this, financial authorities could also consider more qualitative approaches that make use of empirical data that is already available. This could include directly tracking and mapping the financial flows enabling economic activities that are most closely associated with the negative drivers of ETPs, such as land use change in ecosystems with tipping points. Such a mapping of financial exposures could be achieved quite rapidly by implementing mandatory disclosures of financing to companies linked to key drivers of ETPs within recently developed disclosure frameworks, such as the Taskforce on Nature-related Financial Disclosures (TNFD) framework, which emphasises this need for a location-specific approach.[128] Areas where financial flows are linked to ETP drivers represent, firstly, sources of transition risk, because such activities will be vulnerable to future policies and regulations that aim to reverse nature loss. However, where these exposures are not *material* sources of transition risk, individual financial institutions are unlikely to manage them in line with system-wide financial stability concerns, suggesting that a ‘double materiality’ approach is needed by policymakers.[109] Given large-scale ecological breakdown caused by ETPs would result in potentially systemic risks, there is a clear role for financial policymakers to manage such exposures in a precautionary manner, beyond disclosure.

Combining a better understanding of direct exposures to economic activities negatively pressuring ecosystems towards ETPs, with quantitative risk assessments that better account for indirect and non-linear impacts and lack of substitution possibilities, financial policymakers should be in a stronger position to consider appropriate interventions. They could utilise credit, prudential, macroprudential and monetary policy tools to begin to manage the financial risks posed by ETPs, as some central banks have begun to do in relation to sectors most heavily associated with climate change.[vi] Since financing to high-risk activities such as land use change in critical ecosystems is likely to proceed through cross-jurisdictional financial

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[vi] For example, the European Central Bank has begun integrating climate risks into its monetary policy implementation frameworks, such as by limiting carbon intensive assets in its corporate bond purchases and collateral frameworks (ECB 2022)

flows, including tax havens,[133] international coordination will be needed between policymakers, including through existing collaborations, such as the NGFS, or through institutions such as the Bank for International Settlements (BIS) and International Monetary Fund (IMF).

Policy solutions will be successful based on their ability to avoid ETPs being breached *ex ante*. ETPs represent clear 'worst-case' outcomes, or tail risks, of environmental degradation that require a precautionary approach to mitigating risks. Prudential and monetary policy will be insufficient on its own to avert ETPs, since direct pressures on ecosystems arise from a complex array of indirect drivers, only some of which can be addressed through the tools available to central banks and financial supervisors.[45]

This means that financial policymakers will increasingly need to coordinate with other ministries, including those concerned with fiscal, environmental and industrial policy, in order to deliver on their primary mandates.[134] National policies to define an ecological transition, including measures to avoid breaching critical thresholds, must be led by governments. Going forward, central banks and financial supervisors can align monetary and supervisory tools with these broader policies, including the national biodiversity strategies and action plans that will be developed this year in the lead up to CBD COP16 in Cali, Colombia, under governments' commitments to the Kunming-Montreal Global Biodiversity Framework.

Recognising the limits that independent central banks and supervisors face amidst the societal challenges ahead, calls for green fiscal-monetary-prudential coordination have been made by the BIS,[135] among others. Such policy coordination in the face of global emergencies was demonstrated during the response to the COVID-19 crisis.[136] ETPs should be viewed as posing similarly catastrophic threats and serve as a powerful catalyst for such policy coordination and action.

Appendix

Relevant academic literature used to identify key economic sectors implicated in non-climate change pressures on ETPs.

Ecosystem tipping point	**Key drivers**	**Main economic sectors directly implicated in non-climate change drivers**[vii] **(key sectors in bold)**	**References**
Amazon dieback	Land use change Climate change	Agriculture (beef, soy, palm oil, cocoa) Forestry (timber, rubber) Mining Hydropower Oil and gas extraction	Tyukavina et al. 2017; Berenguer et al. 2021; Sonter et al. 2017; Finer et al. 2008; Lapola et al. 2023
Boreal forest dynamics	Climate change Land use change Invasive species	Forestry (timber) Mining Oil and gas extraction Hydropower	Scheffer et al. 2012; Petersen and Sizer 2014; Shvarts et al. 2015; Burrell et al. 2021
Coral reef die-off	Climate change Overexploitation Pollution	Fisheries Aquaculture Agriculture Oil and gas extraction	Zaneveld et al. 2016; Hughes et al. 2017
Mangrove dieback	Land use change Climate change Pollution	Aquaculture (fish, shrimp) Agriculture (rice, oil palm)	Richards and Friess (2016); Friess et al. (2019)
Tropical peatland collapse	Land use change Climate change	Agriculture (palm oil, pulpwood, rubber, rice) Forestry (timber, rubber) Oil and gas extraction	Page et al. 2022; Dargie et al. 2019; Lilleskov et al. 2019; Wijedasa et al. 2017; Garcin et al. 2022

[vii] Economic sectors are regionally specific for ecosystems that span a range of geographies. For example, in Indonesian peatlands the main drivers of land use change are palm oil and pulpwood production. By comparison, the Congo basin peatlands have yet to be substantially developed, but face potential threats from oil and gas extraction, and industrial agriculture.

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About the Institute for Innovation and Public Purpose (IIPP)

The Institute for Innovation and Public Purpose (IIPP) at University College London (UCL) aims to develop a new framework for creating, nurturing and evaluating public value in order to achieve economic growth that is more innovation-led, inclusive and sustainable. This requires rethinking the underlying economics that has informed the education of global civil servants and the design of government policies. Our work feeds into innovation and industrial policy, financial reform, institutional change and sustainable development. A key pillar of IIPP's research is its understanding of markets as outcomes of the interactions between different actors. In this context, public policy should not be seen as simply fixing market failures, but also as actively shaping and co-creating markets. Re-focusing and designing public organisations around mission-led, public purpose aims will help tackle the grand challenges facing the 21st century.

IIPP is a department within UCL – and part of The Bartlett, which consistently ranks in the top two faculties for architecture and the built environment in the world.

About the Global Systems Institute

The Global Systems Institute provides thought-leadership and action-orientated research to drive systems-based solutions to the climate and biodiversity crises. It brings global change researchers from around the world together with industry, policymakers, students and other stakeholders to tackle shared problems, and act as a catalyst that enables translation of this research into applications that deliver tangible and sustainable social and ecological benefit. We aim to better predict global changes through understanding the interactions between the climate, natural ecosystems, human social and economic systems, and the built environment. This will require advancing the state of the art in modelling the Earth system and its sub-systems, including social, economic and engineered (social-ecological) systems. It also requires the full range of experimental, observational, engineering and action research across disciplines. The deep intellectual challenge is to unite several thousand years of global scholarship on what makes for a happy and meaningful human life with the relatively young science of what makes a sustainable Earth system. This means bridging diverse subjects from philosophy, sociology and history, through law, politics and economics, to climate change, Earth system science and the circular economy.

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