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Translating Earth system boundaries for cities and businesses

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Operating within safe and just Earth system boundaries requires mobilizing key actors across scale to set targets and take actions accordingly. Robust, transparent and fair cross-scale translation methods are essential to help navigate through the multiple steps of scientific and normative judgements in translation, with clear awareness of associated assumptions, bias and uncertainties. Here, through literature review and expert elicitation, we identify commonly used sharing approaches, illustrate ten principles of translation and present a protocol involving key building blocks and control steps in translation. We pay particular attention to businesses and cities, two understudied but critical actors to bring on board.

Earth system boundaries (ESBs) define safe and just guardrails for climate, the terrestrial biosphere, freshwater, nutrients and air pollution to maintain a functioning Earth system without incurring significant harm to people[1]. ESBs demarcate the upper limits in the aggregated environmental pressures arising from anthropogenic activities[2–5], including those in the pursuit of aspirational goals such as the UN Sustainable Development Goals. Respecting ESBs requires concerted actions from diverse actors[6], for example, states, cities and businesses, based on a clear and shared understanding of their fair share of resources and responsibilities[7,8]. This means that ESBs need to be translated for actors, which can then inform actors' target setting in ways that consider capacity, responsibility and equity and that involve co-design between science and other stakeholders. Cities and businesses are particularly important actors due to their global

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connectivity, the magnitude of their impact and the potential of their agency[9,10].

Diverse actors are developing science-based targets and methods to do so to respect ESBs[11–13]. Yet critical questions remain. How much action by cities and businesses is required to achieve global goals? What is the fair share of efforts that should be expended by individual cities and businesses to respect the ESBs, with due considerations of their current and historical responsibility, socioecological context and capacity[14,15]?

Cross-scale translation is inherently a complex process involving multiple steps, normative judgements and uncertainties[14–17] arising from the need to account for biophysical, socioeconomic, ethical and cultural dimensions[6]. There is a rich literature on cross-scale translation of planetary boundaries and climate targets to nations, but there is much less work on translations to cities and companies despite their potential to reduce significant pressures on climate, biodiversity and natural resources[9,18]. Furthermore, much cross-scale translation shies away from exploring the ethical and operational consequences of adopted allocation methods. While many cities and businesses have already adopted science-based targets or other forms of targets for climate[9], more widespread uptake of target setting beyond climate change is often hampered by these challenges. Scientifically robust and socially equitable cross-scale translation, a process for allocating globally and regionally aggregated resources, benefits, risks and responsibilities to different actors is needed.

In this Review, we aim to provide clarity on the steps and choices involved in a scientifically rigorous translation of ESBs to businesses and cities. We review literature on cross-scale translation (Supplementary Information 1) to identify emerging sharing approaches and see how they are applied in translation across domains and actors. Our transdisciplinary review draws on translation of global frameworks, including the planetary boundaries[19,20], carbon budgets[21–25] and global biodiversity footprints[26]; likewise, our results are applicable to these and other frameworks beyond ESBs. From this review, and via a structured expert deliberation (Supplementary Information 2), we identify ten general principles underpinning the translation process. We then put forward key building blocks of cross-scale translation and a detailed protocol for cross-scale translation of each ESB. We end by discussing the remaining constraints and possible ways of overcoming them.

Sharing approaches in translation

The 2009 publication of planetary boundaries framework[19] stimulated efforts to allocate shares of a global 'safe operating space' to actors operating at different scales[7]. This process is what we term cross-scale translation, and it can follow top-down[4,27], bottom-up[28] or combined approaches[6,29]. Top-down allocation, also called the 'fair shares' approach[30], involves apportioning global budgets to national, sub-national, sectoral and individual business scales. Climate is the Earth system domain with the most translation applications (for example, ref. 31), which present myriad ways of sharing the global carbon budget accounting for different equity and fairness considerations[4,9,14,22,25]. There are also efforts to adapt the planetary boundary frameworks to the national or regional scale using a bottom-up approach. A bottom-up approach involves determination of a sub-global or local safe operating space and is typically based on nationally or locally relevant variables and boundary values[4,32] such as determining basin-scale environmental water-flow requirements[28,30]. One example is the assessment of boundaries for South Africa based on 20 nationally relevant environmental and social indicators[28]. Other studies have aggregated environmental pressures at a lower scale (industries) to produce environmental pressures at a higher scale (sub-national or national)[29]. Ultimately, a cross-check is necessary to determine whether bottom-up-derived local goals are ambitious enough to meet global goals. The combined approach utilizes both top-down and bottom-up approaches and suggests ways to reconcile differences in the values obtained[29,30].

Our literature review focuses on emerging literature on sharing approaches used within a top-down allocation, which represents the majority of work on cross-scale translations[6,7,24,31,33,34]. We reviewed the scope, scale and sharing approaches used in 40 such studies (Fig. 1, Supplementary Information and Supplementary Table 1). Most translate to supra-national[22,35,36], national[25,36–41], sectoral[21,27,42–51] and product[52–56] levels. One city-scale study focused on consumption footprints of the most populous 62 cities in the Middle East and North Africa[57]. Another made cross-scale translations of responsibilities for managing territorial and global environmental concerns to municipalities in Spain[51]. The three studies of translation to companies comprise a food portfolio of a retail company in France[58], a utility company in Denmark[59] and six companies in Spain[51]. In terms of scope, most studies focus on climate[21,22,25,27,36–42,44–54,57,59–66], followed by freshwater[35–39,41–47,50–52,54,56,57,59–64], nutrient cycles[27,35–48,50–52,54,55,57,59,60,62–68] and the land system[35–40,42,44–47,50–52,54,57,59–66,69], while fewer studies focus on biodiversity[36,40,42,46,51,52,54,58,59,66], oceans[27,40,45–47,50,51,59,63–65] and the atmosphere (beyond climate)[27,44,51]. Some of these studies focus on only one boundary[21,22,25,26,49,53,55,56,58,67–69] while others focus on multiple boundaries[27,35–48,50–52,54,57,59–66].

We have identified 11 sharing approaches used in cross-scale translation: legacy[21,22,27,35,42,43,46–51,53–56,58,63,66], responsibility[25,35,40,42,66], sovereignty[60], economic contribution[21,27,35,44,45,47,49,51,53,55,56], social contribution[49], resource efficiency[66], capability[25,26,35,48,66], basic needs and preferences[21,27,35,42,44,46,48,50,52,53,55,58,59], equality[22,25,27,35–52,57–62,64–67,69], green incentive[48] and development rights[35,66] (Table 1). Some of these approaches represent strong temporal perspectives. For example, legacy and responsibility could represent backward-looking perspectives, capability is focused on the current situation while equality and basic needs can be interpreted as forward looking (Fig. 1). The most commonly applied sharing approaches are equity, legacy, basic needs and preferences, and economic contributions.

Figure 2 shows four ways these sharing approaches are applied:

- A single sharing approach applied to a single scale. This approach allocates directly to the endpoint scale of translation. There are numerous examples where a stand-alone sharing approach is used to allocate national shares, utilizing, for example, the equality (for example, refs. 36,37,61,65,67), legacy (for example, ref. 44), basic needs and preferences (for example, refs. 44,50), capability (for example, ref. 66) and responsibility (for example, refs. 65,66) sharing approaches.
- A single sharing approach applied across multiple scales. This approach allocates initially to intermediate scales before final allocation to the endpoint scale. One study used legacy (grandfathering) (enacted using climate impacts via CO_2-equivalent emissions) to allocate a global carbon budget across multiple scales, to agri-food sectors globally and then at national (New Zealand) scale through to agri-food industries within the country[53].
- Multiple sharing approaches applied jointly at a single scale. This approach involves utilization of at least two sharing approaches in combination to allocate from one scale to another. For example, social contribution through an employment indicator and economic contribution through the gross domestic product indicator have been jointly applied to allocate a carbon budget from national to industry scale[49].
- Multiple sharing approaches applied across multiple scales. This approach uses a unique sharing approach for each cross-scale allocation, thus going through one or several intermediate scales[44,45,47]. For example, one study applied equality in translating from the global to the national scale, followed by the use of an economic contribution sharing approach enacted via gross value added in the translation from the national to the industry scale[45].

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Fig. 1 | The scope, scale and sharing approaches in cross-scale translation. The horizontal axis shows sharing approaches as applied in 40 translation studies cross-tabulated against biophysically defined boundaries on the vertical axis. The asterisks indicate transgressed boundaries at the global level[19,20]. Boundaries for biosphere integrity, land-system change, freshwater use, nitrogen and phosphorus cycles and atmospheric aerosol loading are sub-global. The numbers in each coloured circle indicate the number of studies that applied the relevant sharing approach (as a stand-alone or as part of a bundle) for the particular boundary and categorized by the relevant scale of translation (intermediate or end scale) for that step. The legend shows the endpoint scale of translation and its respective number of studies. The sharing principles are positioned on a sliding scale of inherent temporal perspectives. The total number of studies per boundary or per sharing approach exceeds 40 because many studies translate for multiple boundaries utilizing bundles of sharing approaches (Supplementary Table 1).

Note that the frequency of application is not an indication of the 'appropriateness' of a translation as the choice among sharing approaches may be affected by many factors, including data availability, practicality and the perceptions of fairness of those conducting the analysis[14]. For example, as the application of sharing approaches depends on data availability at the requisite scale, there is a risk that scholars and practitioners may prioritize sharing approaches for which data exist or simply use approaches that are already widely used (the authors of the 40 studies are overwhelmingly from the Global North) over sharing approaches that could lead to more suitable or equitable translations. Although these are pragmatic decisions of a young research field in the short term, they should not be perpetuated into practice without clear understanding of the assumptions and limitations. There is a need to establish clear principles, guidelines and inbuilt transparency on assumptions. With this goal in mind, we have developed basic principles and a protocol to help support choices for cross-scale translation.

Ten principles of translation

We present ten principles for translation identified through a structured expert deliberation (Fig. 3). These principles relate to the process (1–4), the outcome as translated shares and targets (7–10) or both (5 and 6) of cross-scale translation.

Principles 1 and 2 point to the need for consistent and reproducible approaches with scientific rigour, ideally based on well-established, peer-reviewed literature that also reflects perspectives from the Global South. Translation also needs to transparently provide justifications for important operational decisions and explain sources of uncertainty. These two principles provide foundations needed for granting scientific legitimacy to the translation process, especially regarding decisions that are necessarily subjective. Crucially, the principle of transparency calls for a very explicit consideration of the normative positions (for example, the rationale for allocation and adjustments, who is proposing it and why), as well as transparency in the procedure of allocation. Relatedly, Principle 3 emphasizes the need to consider how normative decisions regarding allocation and adjustments have justice implications. It stipulates that the trade-offs in distribution of resources and risks, across geographical locations or between current and future generations, need to be considered[70]. Principle 4 calls for systems thinking in the translation process as well as the allocation outcomes. Interactions between Earth system domains need to be considered because several pressure points can combine to produce larger effects, and actions that take place in one location can have consequences at different scales[9]. For example, a decision to clear some forests in the Amazon basin should consider its impact on local biodiversity due to habitat fragmentation (biosphere: natural ecosystem area ESB) and rainfall patterns in Brazil and beyond[71]. Among the important system attributes are metacouplings[72], with cities and companies benefiting from and influencing ecosystems and their services locally and globally[10,73].

Principle 5 states that the translation process and allocation outcomes should err on the side of stringency in line with the general precautionary principle. This would imply factoring in an appropriate buffer in the starting budget, adjustment ranges or the allocated shares or responsibilities[10]. Principle 6, related to context sensitivity, suggests that local conditions should be used as inputs for the allocation and adjustment step(s). Conditions for different cities and companies vary drastically in environmental, demographic, social, economic and political dimensions, and these differences are often very relevant for determining an equitable allocation of shares of resources and responsibilities.

Fulfilling Principles 3 and 6 may require the introduction of an additional adjustment step to the allocation procedure, where initially allocated shares are redistributed on the basis of additional sharing approaches. For example, a 'capability' approach would focus on allocating shares to reduce current and future environmental impacts on the basis of the capacity to take action, while 'responsibility' would account for historical environmental impacts generated by different entities.

Table 1 | The 11 sharing approaches in cross-scale translation and their enacting metrics

Sharing approach	Description	Example of enacting metrics
Legacy	Shares are in proportion to current or historical entitlements, ecological impacts or environmental footprints generated by the entity (also referred to as grandfathering).	Consumption footprints, production footprints, product footprints
Responsibility	Shares are allocated by accounting for cumulative impacts and emissions or environmental footprints over time (that is, historical debt of individuals, nations, cities, sectors, businesses).	Historical pollution discharges, emissions or land clearing; renewable energy installation
Sovereignty	Shares are in proportion to the current stocks and flows of natural capital in possession within territorial boundaries.	Cropping land and plantations; renewable and non-renewable resource stocks; ecosystem biocapacity
Economic contribution	Shares are allocated in proportion to the current economic contribution of the country, sector, industry or company, for example, measured in contribution to gross domestic product.	Gross value added or gross domestic product; company or sectoral production volume; company operating revenues
Social contribution	Shares are allocated in proportion to the current contribution of the sector, industry or company to communities and wider society, for example, measured in numbers of people employed.	Number of full-time-equivalent employees; expenditure on wages and salaries; financial contribution to community programmes; taxes paid
Resource efficiency	Shares are determined for countries (or sub-national regions) on the basis of their current resource use efficiency relative to the global average level, benefiting those with higher efficiency, or where the largest efficiency gains can be expected.	Resource use per area of land, product, service or economic output
Capability	Shares are allocated by accounting for the ability of an actor to take actions based on relative capabilities as a basis, for example, through financial means.	Wealth; governance effectiveness; renewable energy growth capacity; regenerative agriculture capacity
Basic needs and preferences	Shares are allocated such that fulfilment of human basic needs comes first, before distributing the rest of the resources to other non-basic needs.	Nutrient and water required to grow regionally suitable staple food; calorific content of food; food nutrient adequacy
Equality	Shares are in proportion to population size of the country, region or city.	Population (per capita); total output (per dollar of output); disposable income (per dollar of income)
Green incentive (merit)	Shares are allocated in a manner that incentivizes or rewards companies with low emission intensity or higher shares of renewable energy use.	Emission intensity; share of renewable energy in energy input mix; voluntary environmental sustainability activities or programmes
Development rights	Shares are allocated by accounting for the socioeconomic context of the country, in particular, the resources required to lift people out of poverty in the future.	Poverty rate; development level; other socioeconomic indicators

Sharing approaches are enacted by metrics and datasets, harmonized at the appropriate scales to ensure consistency (for example, countries, sub-national, cities, industrial sectors and businesses). While some sharing approaches have been interpreted as being related to one another[24], we list them separately here to clarify their meaning and intended usage in cross-scale translation.

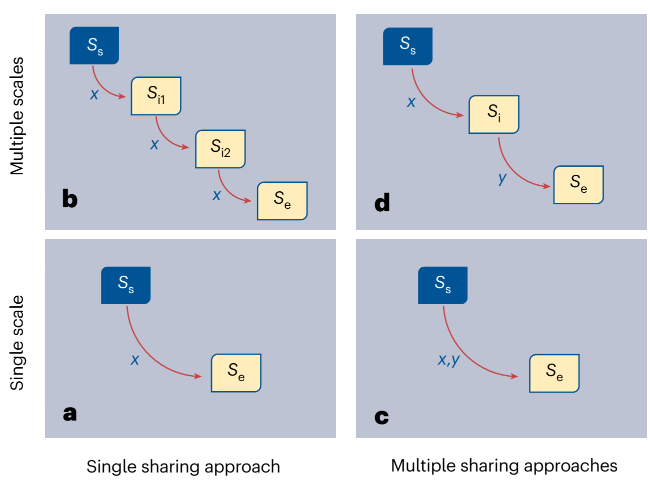

Fig. 2 | A typology of cross-scale translation as revealed from combinations of sharing approaches applied at a single scale or across multiple scales. **a**,**b**, A stand-alone sharing approach, x, applied to a single scale, S_e (**a**) or across multiple scales, S_{i1}, S_{i2} and S_e (**b**). **c**,**d**, A mix of sharing approaches, x and y, applied jointly at a single scale, S_e (**c**) or sequentially across multiple scales, S_i and S_e (**d**). S_s and S_e represent start and end scales, respectively, and S_{i1}, S_{i2} and S_i indicate intermediate scales.

Principle 7 is about communication and implementation, stipulating that the outcomes of translation should be simple enough to allow understanding and universal enough to allow for alignment and decision-making under different local contexts. Principle 8 suggests that the outcomes of translation and subsequent targets are set in such a way that incentivizes actors to raise their level of ambition for sustainability. As staying within ESBs is a long-term process, incentives are needed to inspire actors to make persistent efforts throughout, to become 'pioneers' and to help 'laggards' to catch up. Principle 9 highlights the importance of time-bound translation and target setting and specifying a priori how the allocated shares and targets can be updated in a rigorous manner to reflect progress in scientific understanding and the evolving socioeconomic and environmental context. Finally, Principle 10 stresses the need to maximize synergies among targets and minimize trade-offs such as negative externalities and to ensure that disruptive and exploitative power dynamics are avoided. For example, cities and companies typically set targets separately, but alignment is needed[10]. As synergies and trade-offs are very common, nexus approaches that connect various targets, associated influencing factors and effective governance structures are particularly promising to help operationalize this principle[74] and ensure actors are held accountable for negative externalities even if unintended.

Key building blocks linking ESBs to actors

Building on previous work[4,75], Fig. 4 presents key building blocks of cross-scale translation and subsequent target setting.

Transcription

ESBs are based on the state of Earth system functions, related to global warming (climate), aerosol optical depth (atmosphere), hydrological

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Translation process

P1 Scientifically rigorous The approach/application is consistent, quantitative and evidence based, with reproducible quantitative outcomes. It includes clear description of the methodological steps, an account of key underlying assumptions and remaining sources of uncertainty.	**P2 Transparent** The approach/application clearly and sufficiently explains the rationale for allocations, being explicit about underlying assumptions and normative considerations. In addition, the data used are accessible to other interested parties.	**P5 Sufficiently safe** The approach/application and the outcomes include some buffers in the allocated shares or responsibilities, as an additional level of stringency.	**P7 Enabling** Targets are (1) universal enough for alignment yet allow local decision-making, (2) pragmatic for implementation (feasible measurement and controllability) and (3) simple enough to facilitate communication and understanding by different stakeholders.	**P8 Incentivizing** Targets are presented in a manner that incentivizes action by actors under different circumstances. Specifically, those actors who are 'pioneers' are emboldened to set more ambitious targets, while 'laggards' have suitable pathways to catch up.
P3 Just The approach/application incorporates elements of intergenerational and intragenerational equity implemented as adjustment(s) to initially allocated shares and considers the potential negative implications of translated targets on key societal goals (for example, Sustainable Development Goals).	**P4 Systemic** The approach/application considers potential consequences on other parts of the Earth system arising from setting specific targets specifically focused on one part. It also considers teleconnections/telecouplings that have potential for unintended negative consequences on key societal goals (for example, Sustainable Development Goals).	**P6 Context sensitive** The approach/application and the outcomes take into account environmental and socioeconomic context. While the aim is to foster global alignment, it allows for locally devised strategies/actions (it is not overly prescriptive).	**P9 Dynamic and time bound** Targets are time bound but also able to reflect the dynamic nature of 'safe and just' operating space and its context. This includes the possibility of updating/adjusting targets in response to the development of the underlying Earth systems science.	**P10 Synergetic** Targets are set so that potential co-benefits in other Earth Commission domains, as well as societal goals (for example, Sustainable Development Goals), are recognized and amplified. Conversely, targets are set so that potential negative externalities and unjust power imbalances are avoided.

Translated shares and targets

Fig. 3 | Ten principles of translation. Principles (P) 1, 2, 3 and 4 are on translation processes, Principles 7, 8, 9 and 10 are on translated shares and targets, with Principles 5 and 6 on both.

flow alteration (surface water) and the rate of resource renewal (groundwater), area of natural and semi-natural ecosystems (terrestrial biosphere), and nutrient concentrations or surplus (nutrient cycles)[1]. To operationalize ESBs, these boundaries need to be linked to anthropogenic pressures[4]. Generally, this is done by expressing maximum quantities of pollutants and resource uses (for example, in kg yr^{-1}) that can then be partitioned and distributed to, and managed by, cities and businesses. This process of attributing the links of the boundary quantities to the pressure indicators is what we call transcription. The transcribed anthropogenic pressures we refer to as Earth system budgets[9].

Allocation

Allocating transcribed Earth system budgets to actors involves a two-step process: scaling and adjustment, each involving appropriate sharing approaches. Scaling distributes the Earth system budget across scales relevant to the actor, and it may involve sequential distribution from one scale (for example, global) to intermediate scale(s) (for example, country, industry) through to the endpoint scale (for example, cities or businesses). For most ESBs, the budget-scaling step will be a form of downscaling, but for ESBs constructed at a finer scale, for example, grid-based boundaries (biosphere: functional integrity), the process can be a form of upscaling. It is important to consider within what geographical extent such scaling and subsequent adjustment should take place (Box 1).

The adjustment step re-distributes the initial shares resulting from scaling among actors within the same scale, to account for equity considerations (Principle 3) and differences in their social, ecological and economic contexts (Principle 6). For example, one possible way of adjusting resource allocation among a group of cities is to develop a typology based on their socioeconomic and ecological context and use the typology to produce city-specific adjustment factors that can then be applied to their initially allocated budget.

Both the scaling and adjustment steps can occur multiple times and can utilize bundles of sharing approaches in line with the reviewed literature. For example, an initial allocation can be calculated to the minimal unit (for example, individual person, land unit, economic output unit) appropriate for the ESB, then aggregating this per unit budget up to the intermediate or endpoint scale[48,52,58]. Adjustments can be made at each scale[51]. Different combinations of sharing approaches can be applied in these steps, reflecting different values of what is considered equitable and fair. The result of allocation is a set of translated shares of the Earth system budgets to actors, underpinned by a scientifically robust (Principle 1), transparent (Principle 2), just (Principle 3) and context-sensitive (Principle 6) process.

Target setting and alignment checking

The translated shares can be used to inform target settings by different actors, as well as benchmarking against individual actor's current or future impacts. All actors generating environmental impacts should set appropriate science-based targets for impact reduction[11]. For actors who already have targets in place, benchmarking can inform whether their targets are ambitious enough to remain within their share of the ESBs. Alignment checking is the procedure to ensure individual targets adhere and align with their translated share or that, in aggregate, targets adhere and align with the ESBs. Although outside of the direct scope of cross-scale translation, these steps are crucial for operationalizing ESBs and ensuring accountabilities (Fig. 4).

A protocol for translation

In pursuit of stronger consensus, transparency and comparability in terms of how cross-scale translation is conducted, here we present a protocol of translation that incorporates several key decision points on the basis of three physical properties of the boundaries[41]: spatial construct, current state and regenerative nature; temporal perspective and suitability of sharing approaches; and enacting metrics and data.

Spatial construct of the boundary

The spatial construct of the boundary is the first key decision point, determining how allocation proceeds following transcription. The transcribed budgets for globally constructed boundaries (for example, climate change) can be downscaled to sub-global actors or intermediate scales through cross-scale allocation; (bio)regionally constructed boundaries, including those defined at the local scale (for example, nutrient cycles), basin scale (for example, surface water, groundwater), biome scale (for example, forest cover) and ecoregion scale (for example, natural ecosystem area) are either upscaled or downscaled as required, and grid-based boundaries (for example, biosphere functional integrity) are aggregated to actor scales.

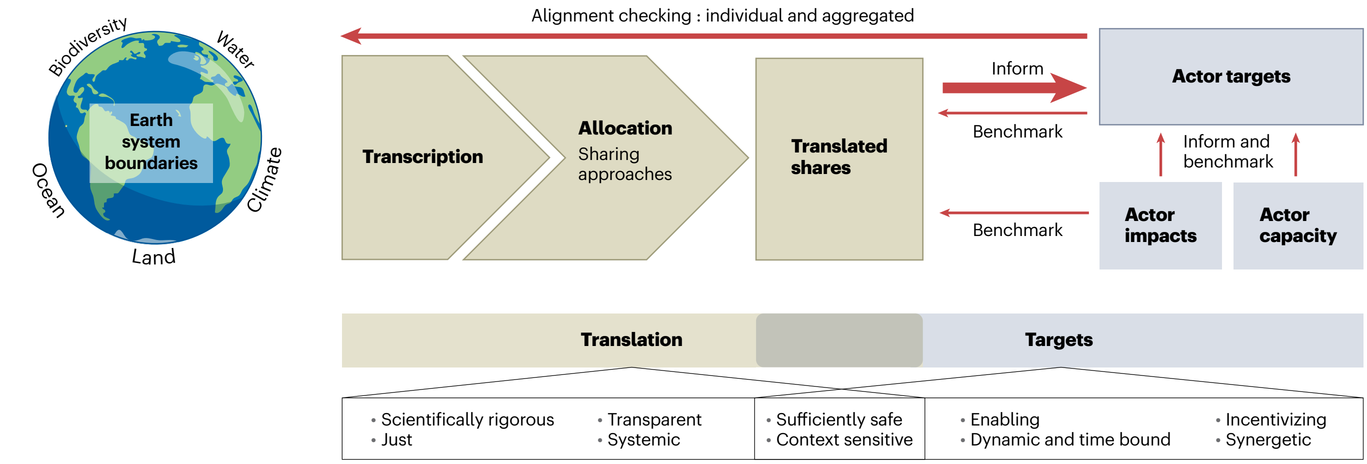

Fig. 4 | Key building blocks in connecting ESBs to actors and the applicable ten principles of translation. Cross-scale translation comprises sequential processes of transcription and allocation to derive translated shares for individual actors. Transcription converts ESBs into indicators of anthropogenic pressures in units that are used by actors to measure their impacts. The transcribed ESBs are then allocated to actors via the application of different sharing approaches (Table 1) as appropriate. Translated shares can be used for target setting, informed by the actor's impacts and capacity for action, or benchmarking against impacts or for alignment checking.

BOX 1

Bioregional versus global citizen's perspective

Translating ESBs with regionally defined pressures and/or states can be done within two different system boundaries—sharing within the region or taking a global citizen's perspective. For example, the ESB for surface water resources has a global boundary (the global total withdrawable amount of surface water) as well as regional or local boundaries (a basin total withdrawable amount that does not exceed 20% of average flow)[1,8]. Given the strong regional characteristics of water resources, a bioregional approach (sharing local boundaries among the people and economic activities within the basin) would seem reasonable, which can also ensure that the global boundary is met[56].

However, a bioregional approach alone is insufficient and needs to be complemented by a global citizen's perspective (sharing the global total budget for anthropogenic consumption across the world population equally and using it as a reference point for benchmarking or further adjustment based on context or capacity). A bioregional approach towards resource sharing rewards those with natural endowment (a country or city located in a resource-abundant region with a comparatively small population) while penalizing those located in water-stressed regions and/or those with high population. This approach may also produce an unintended loophole as the globally connected production and consumption system means a region can shift its environmental burden elsewhere (compensate for its high water consumption through embodied water without breaching its local boundary)[85].

Similarly, a bioregional approach is inappropriate when it comes to sharing responsibilities. For example, regions that are rich in biodiversity are often concentrated in the Global South and often include territories owned/managed by indigenous communities. A bioregional approach in meeting the natural ecosystem area goal may place the entire burden on local communities and stakeholders[86] while the benefit is shared globally. In such a case, a globally shared responsibility, considering factors such as current needs and rights[85,87], historical responsibilities[88,89] and telecoupled system impacts[90], would be much more appropriate. Beneficiaries of ecosystem services should financially contribute towards investments in ecosystem protection and restoration via mechanisms such as payments for ecosystem services, biodiversity-related taxes, fees and charges[91]. Therefore, translating through a bioregional approach needs to be accompanied, benchmarked or adjusted by a global citizen's approach to inform target setting and policy development. Actors should strive to adopt the more stringent target.

State of the boundary

The status of the ESB[1,20] is the next decision point as it determines whether there is Earth system budget to share or Earth system deficit responsibility to allocate. For ESBs that have not yet been transgressed, allowable aggregated pressures can be allocated. For ESBs that have already been transgressed, associated mitigation and abatement responsibilities need to be allocated.

- For the climate boundary (globally constructed), it is well established that we are on a pathway to transgressing a 1.5 °C level of global warming within the next ten years without drastic reductions in GHG emissions[76]. While the 1.5 °C boundary has not yet been exceeded, current emissions far exceed the annual carbon budget transcribed to the boundary. Accordingly, the focus would be on burden sharing (allocation of reductions responsibilities), rather than distributing diminishing resource budgets.
- For (bio)regional boundaries, transgression is assessed at the scale of each boundary construct, with actors' impacts possible from both within and outside of the region. When the boundary is defined as spatially discrete, restoration in one region does not offset degradation in another, regardless of the similarities in ecosystem services, for example, biosphere boundaries based on unique ecoregions, nutrient cycle boundaries based on water quality criteria connected to nutrient flows from agricultural lands, and freshwater boundaries based on annual groundwater recharge rates, environmental flow criteria or monthly flow alteration allowances. Transgression status

is assessed per region but impacts (and actions) can be assessed at smaller or larger scales. With the surface water boundary assessed monthly, transgression might occur in every or only some months of the year.
- For boundaries where transgression is assessed on a grid-by-grid basis, there could be both transgressed and non-transgressed grids within the territorial boundaries of nations or cities, or within the spatial range of impacts from businesses, located either within or outside of the given grid.

ESB transgression status also informs the choices regarding temporal. Backward-looking sharing approaches are appropriate for allocating the reduction space of transgressed boundaries as they account for actors' past impacts and degree of responsibility for the current state of transgression. Returning to the safe space also entails sharing resources in the face of a collective need to reduce impacts. For this reason, forward-looking sharing approaches are also appropriate as they account for the different development rights or needs of actors to the resource, as well as the capabilities of actors to take action in reduction, restoration and regeneration. However, when ESBs are not (yet) transgressed, the main concern is the just allocation of limited resources utilizing the forward-looking approaches.

Regenerative nature of the Earth system domain
The approximate rate at which the state of the Earth system domain regenerates is another key factor determining suitable sharing approaches. We categorize the regenerative capacity as zero or none, slow or rapid.

- For Earth system domains with no regenerative capacity (non-renewable and/or have irreversible impacts), reducing or even halting impacts does not alter the state of the boundary. For example, CO_2 emissions are cumulative in nature with almost no regenerative capacity. Reducing the emissions will not result in cooling to pre-industrial temperatures on policy-relevant timescales.
- Earth system domains with slow regenerative capacity are able to renew and restore at approximately decadal timescales. The regenerative rate of nitrogen and phosphorus concentrations in water bodies can be considered slow, at the timescale of nutrient cycling through soil. Similarly, the regenerative rate of groundwater is along the timescale of aquifer recharge. The regenerative rate of the biosphere can also be considered slow, along the timescale of vegetation growth and ecosystem recovery.
- Earth system domains with rapid regenerative capacity renew or recur at approximately seasonal or annual timescales. Background levels of aerosols are considered to renew rapidly as their concentrations in the air would drop to background levels in a matter of months or less after a hypothetical cessation of emissions. Anthropogenically available surface water budget is considered to regenerate rapidly as it replenishes annually following the seasonality of precipitation.

Temporal perspective and suitability
The temporal perspective is the final decision point before connecting to the pool of suitable sharing approaches. We categorize the temporal perspective as forward looking, current and backward looking.

For domains with no or slow regenerative capacity on policy-relevant timescales, even if all actors shift to sustainable practices, restoration/renewal is either not possible or very slow and uncertain. Therefore, backward-looking sharing approaches are appropriate since past actions are reflected in the current status of the boundary. For rapidly regenerative domains, backward-looking sharing approaches are less relevant as past actions have little impact on the available resources going forward. For all domains, regardless of regenerative rates, forward-looking sharing approaches are suitable as either already-exceeded or limited resources must be allocated, and future actions on reductions should consider actor capabilities. When applied to specific domains, this means the following:

- For climate, backward-looking sharing approaches are appropriate for allocating emission reduction responsibilities, and forward-looking sharing approaches are appropriate for allocating limited remaining global budgets as well as reduction responsibilities for upholding trajectories that are essential for ESBs.
- For biosphere, nutrients, groundwater, backward-looking sharing approaches are suitable for allocating reduction and restorative responsibilities as past impacts affect current resources and concentrations. Forward-looking sharing approaches are needed to allocate land use on the basis of needs and developmental rights, to allocate restorative actions on the basis of capability, to allocate regionally exceeded or limited nutrient flows and groundwater on the basis of needs and reduction possibilities on the basis of capability.
- For aerosols and surface water, past actions are less relevant to the current state of the resource, and transgression last year does not mean transgression this year. Focus should rather be on allocating the limited resource equitably on the basis of needs and rights to development, and conservation actions on the basis of capability, using the forward-looking sharing approaches.

The choices following all the preceding decision points lead to different pools of suitable sharing approaches (Fig. 5), each reflecting different temporal perspectives. The final choice of sharing approaches reflects different perceptions and value judgements on what is fair (Principle 3) and may change with varying and evolving context. Each allocation according to a sharing approach will inevitably come with its own trade-offs and inbuilt biases, where moving towards equity in one aspect can move away from attaining equity in another and where choices in the sharing approaches might favour or disfavour certain actor types over others. Thus, multiple sharing approaches often need to be incorporated into translation approaches to better approximate Earth system justice.

Enacting metrics and data
Once sharing approaches are determined, appropriate enacting metrics, defined as suitable indicators to represent environmental and socioeconomic aspects (for example, rates of resource utilization and impacts, natural resource endowment, levels of socioeconomic development or current status of the Earth system domain; Table 1), need to be identified to implement allocation. For example, the capability-sharing approach has been interpreted in terms of the enacting metric of governance effectiveness[25], wealth and economic value[14,22], and renewable energy capacity[25] in the literature. For sharing the burden of reducing aggregate pressures, environmental footprint metrics are relevant for enacting responsibility-based sharing approaches. For sharing an available Earth system budget, human well-being metrics are relevant for enacting needs-based sharing approaches, economic metrics are relevant to enact capability-based sharing approaches and population metrics, current or projected, are relevant to state actors to enact the equality principle[77].

For each enacting metric, datasets are required at the scale of the translation intermediate or end scales; however, these data are not always available or cannot be readily applied to different kinds of actors. Hence, in practice, the choice of sharing approaches is heavily constrained by data availability (for example, ref. 51). While globally consistent and longitudinal datasets that cover most of the 11 identified sharing approaches are available at country scale from data portals such as The World Bank, United Nations Development Program, and Food and Agricultural Organization, consistent data at city and

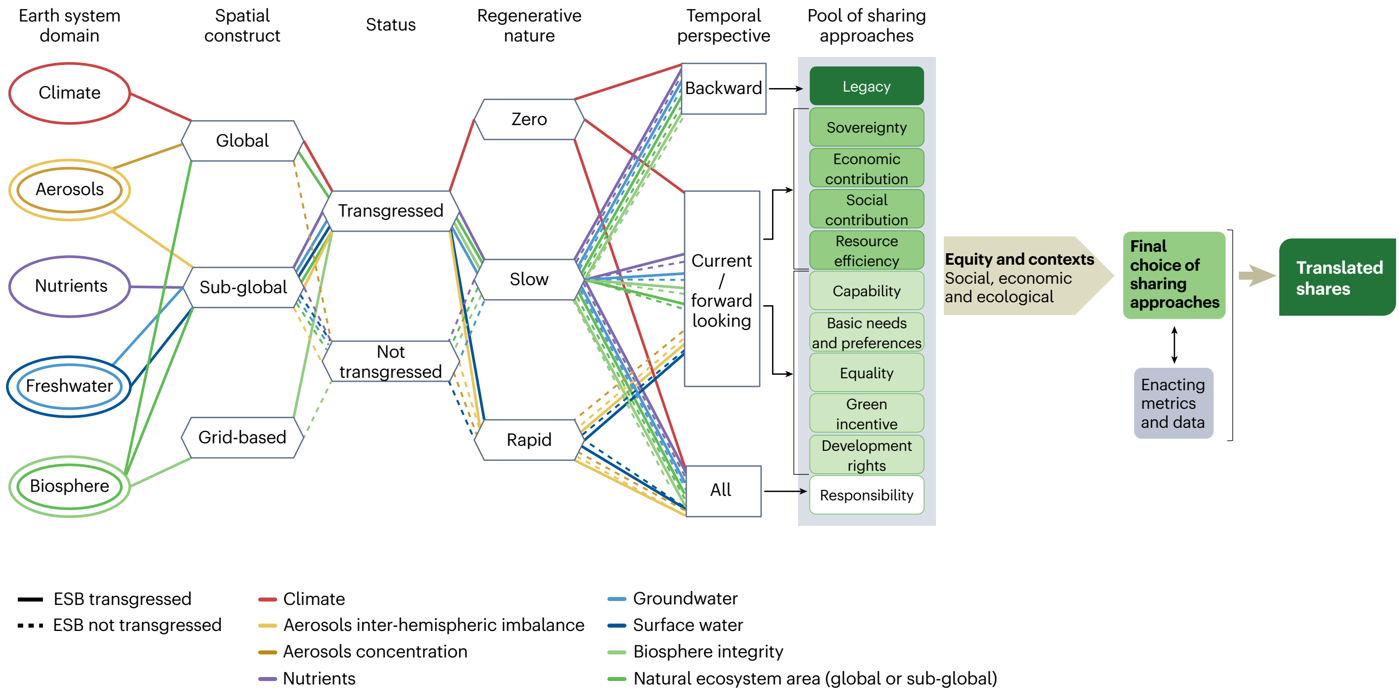

Fig. 5 | Towards a protocol for cross-scale translation of ESBs. Key decision points in ESB cross-scale translation pertaining to the Earth system domain, spatial construct of the boundary, the current status of the boundary, the regenerative nature of the boundary on policy-relevant timescales and applicable temporal perspective for sharing. These aspects can guide towards a pool of sharing approaches (shown in different green shades) from which an actor can choose followed by considerations of equity and actor's specific contexts, as well as choice of enacting metrics informed by available data, before arriving at the final choice of sharing approaches. Applying the final set of sharing approaches would produce allocated shares for the respective Earth system domains.

business scales are limited. Where data are available at the desired scale, they often cover only the capital city and largest city in each country[78] and specific industrial sectors[79]. Furthermore, data at company scale are typically self-reported (if reported at all) and compiled by organizations on a voluntary basis, such as those compiled by the Carbon Disclosure Project (https://data.cdp.net/), often requiring further process to ensure consistency and comparability[80]. Consistency and comparability of data across the same scale are particularly important for the adjustment step. Data collection and harmonization, particularly at sub-national, city, sectoral and organizational scales, are critical to enable the implementation of most suitable and equitable sharing approaches.

Our proposed protocol lays out a step-by-step approach in cross-scale translation. In some cases, the same results can be achieved by integrating multiple steps into one when building a quantitative model to implement the translation. For example, a weighted approach that considers impact, equality and capacity to derive a weighted combination in allocating carbon mitigation targets[25] can achieve the same result mathematically as following three distinctive steps of cross-scale allocation and two adjustments. Both approaches are technically robust and can be made transparent. We chose a step-by-step approach in our protocol as it might be easier for practitioners to adopt and build upon, with intermediate results being made visible to highlight the impacts of choosing different sharing approaches. For example, using an equal per capita sharing approach as the first step of cross-scale allocation gives a global average citizen's share, which is an important result in its own right.

Remaining gaps and next steps

The ultimate goal of the cross-scale translation is to link biophysically defined boundaries of Earth systems to actors, informing their target setting, policy making, implementation and benchmarking. By synthesizing existing approaches, building common principles and protocols, this Review aims to ensure the translation is robust, transparent, fair and comparable across domains and geographies. Several important issues need to be kept in mind in applying the protocol and grounding decisions on the translated shares.

First, to ensure transparency and comparability, it is vitally important for any translation attempts, by individual cities, companies or researchers assisting these actors, to present the translated shares together with step-wise decisions made, for example, along the protocol presented in Fig. 5. Any additional considerations and assumptions that may influence the outcome, for example, type of cities or businesses[81], should also be clearly noted.

Second, to make the actor-level shares and goals comparable and compatible with each other and to ensure the sum aligns with the global total, it is desirable to have a group of cities and companies (for example, an international city network, cities in a country and companies within a value chain and/or industry sector) adopt the same methods and allocate/adjust collectively rather than encouraging individual actors to pick and choose methods. Organizations such as Science-Based Targets Network and Science-Based Target initiative, global city networks such as C40 Cities Climate Leadership Group, Local Governments for Sustainability and World Business Council for Sustainable Development can play important roles in piloting the process. Note, however, that the transparency of company targets approved by Science-Based Target initiative must be improved[82] to comply with the ten principles developed here, pointing to the need for a global standard similar to ISO (International Organization for Standardization) 14064.

Third, given the plurality in translation methods, in particular the many sharing approaches, there is a risk of individual actors cherry-picking methods in translation and subsequent target setting. While adopting almost any method of translation will deliver a directionally appropriate target for individual cities or companies[83], ensuring absolute sustainability at a planetary level[33,34,46] requires the aggregated individual shares to remain within the ESBs. As long as the same method is used to translate across all cities and companies in the world, absolute sustainability can be ensured. However, in practice, this is not always realistic or feasible. To reduce the risk of the aggregated target breaching the ESBs, when a city or company attempts to conduct the translation individually instead of within a network of actors, these actors should be encouraged to employ several different methods of sharing/adjustments, be transparent about the methods adopted, compare the results and use the more stringent ones to inform their own target setting and other decision-making[9]. Such individual choices should also withstand independent external reviews for robustness and accountability.

Translating and operationalizing ESBs for national and sub-national actors to set science-based targets is still at its early stage. There are many challenges and knowledge gaps. For example, the uncertainties involved with nonlinear interactions among different boundaries[84], the consequences of different choices of sharing principles and procedures, the dynamic nature of some boundaries and socioeconomic contexts and unclear governance and accountability mechanisms[9]. Some of the challenges are inherent to the complexity of cross-scale translation (for example, incomplete state-pressure causal links), some are domain specific and others are related to the end users and their interactions with each other (for example, reconciling different approaches for cities and companies).

The principles and protocol proposed here are the first step towards developing a fully coherent and transparent procedure for translation, which needs to be extended and tested with quantitative models under each sharing principle and in real-world settings. Going forward, several important tasks and questions need to be tackled in linking ESBs to cities and businesses. These include the need to (1) complete the state-pressure links for all ESBs to facilitate the transcription step, (2) integrate cities and businesses into the same translation framework to avoid leakage or double counting between cities and businesses, (3) develop methods that can incorporate or handle the interconnectedness across all ESB domains, (4) enhance comprehensive and comparable data availability, (5) develop concrete guidance and standards to assist cities and companies in their translation and science-based target setting and (6) develop effective governance and accountability mechanisms to assess compliance and ensure ESBs are not transgressed.

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Competing interests

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Additional information

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