

Commentary

Many risky feedback loops amplify the need for climate action

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Many feedback loops significantly increase warming due to greenhouse gas emissions. However, not all of these feedbacks are fully accounted for in climate models. Thus, associated mitigation pathways could fail to sufficiently limit temperatures. A targeted expansion of research and an accelerated reduction of emissions are needed to minimize risks.

As we increasingly understand climate change as a series of disasters in the short term and a major threat in the longer term, many governmental jurisdictions and world scientists have declared a climate emergency.¹ In addition, nearly all countries have signed on to the Paris Accord, which calls for limiting warming to 2°C, and ideally 1.5°C. One of the main factors making climate change especially dangerous is the risk of amplifying climatic feedback loops. An amplifying, or positive, feedback on global warming is a process whereby an initial change that causes warming brings about another change that results in even more warming (Figure 1). Thus, it amplifies the effects of climate forcings—outside influences on the climate system such as changes in greenhouse gas concentrations. In part because of positive climate feedbacks, a very rapid drawdown in emissions will be required to limit future warming.

Ultimately, even relatively modest warming is expected to increase the risk that various climatic tipping points will be crossed—causing large changes in the future state of Earth's climate system, thereby adding further amplifying feedbacks.² Despite major recent progress in incorporating a host of interacting feedbacks,^{3,4} climate models may still be underestimating the acceleration in global temperature change that a large and inter-related set of amplifying feedback loops and tipping points could cause. In a likely

short-term scenario, our lack of dramatic emission reductions could result in a future with ongoing and intensifying climate impacts. In the worst case long-term scenario, interactions among feedback loops could result in an irreversible drift away from the current state of Earth's climate to a state that threatens habitability for humans and other life forms.⁵ In any case, the accuracy of climate models is of vital importance since they guide climate mitigation efforts by informing policymakers about the expected effects of anthropogenic emissions.

Here, we discuss feedback loops in the context of climate science, present an extensive list of diverse feedbacks, and consider implications for climate research and policy.

Feedback loops and the remaining carbon budget

The remaining carbon budget is defined as the permitted amount of future anthropogenic carbon dioxide (CO₂) emissions that are consistent with a given climate target and provides a direct link between climate science and climate policy, as it can guide emissions targets.^{4,6} It is closely related to the transient climate response to cumulative emissions of carbon (TCRE), which characterizes the relationship between cumulative CO₂ emissions from the present day and warming due to CO₂ emissions relative to preindustrial levels.⁶ Although highly un-

certain, the remaining carbon budget associated with 1.5°C warming was recently estimated to be 260 Gt CO₂ relative to the start of 2023, which could be exhausted in just 6.5 years.⁷ If their combined effects are underestimated, the additional climate feedbacks could further reduce the remaining carbon budget.

Positive climate feedback loops lead to greater warming per unit of CO₂ emitted, thereby substantially increasing the TCRE and reducing the remaining carbon budget. However, it is often difficult to accurately model Earth system feedbacks. A recent major TCRE assessment⁴ used expert judgment to account for limited coverage of Earth system components (e.g., certain biological feedbacks), arriving at a relatively wide “likely” interval of 1.0°C–2.3°C per 1,000 Gt C. Despite the clear importance of understanding positive feedbacks, the scientific understanding of the unrepresented Earth system positive feedbacks has been characterized as “very low.”⁶ Thus, better characterization of climate feedback loops is necessary to more accurately estimate the remaining carbon budget.

Many risky feedbacks

Here, we present, to the best of our knowledge, the most extensive list available of climate feedback loops (Tables 1, S1, S2, and Figure S1). In total, we have identified 41 biogeophysical feedback loops (20 physical and 21 biological), including 27



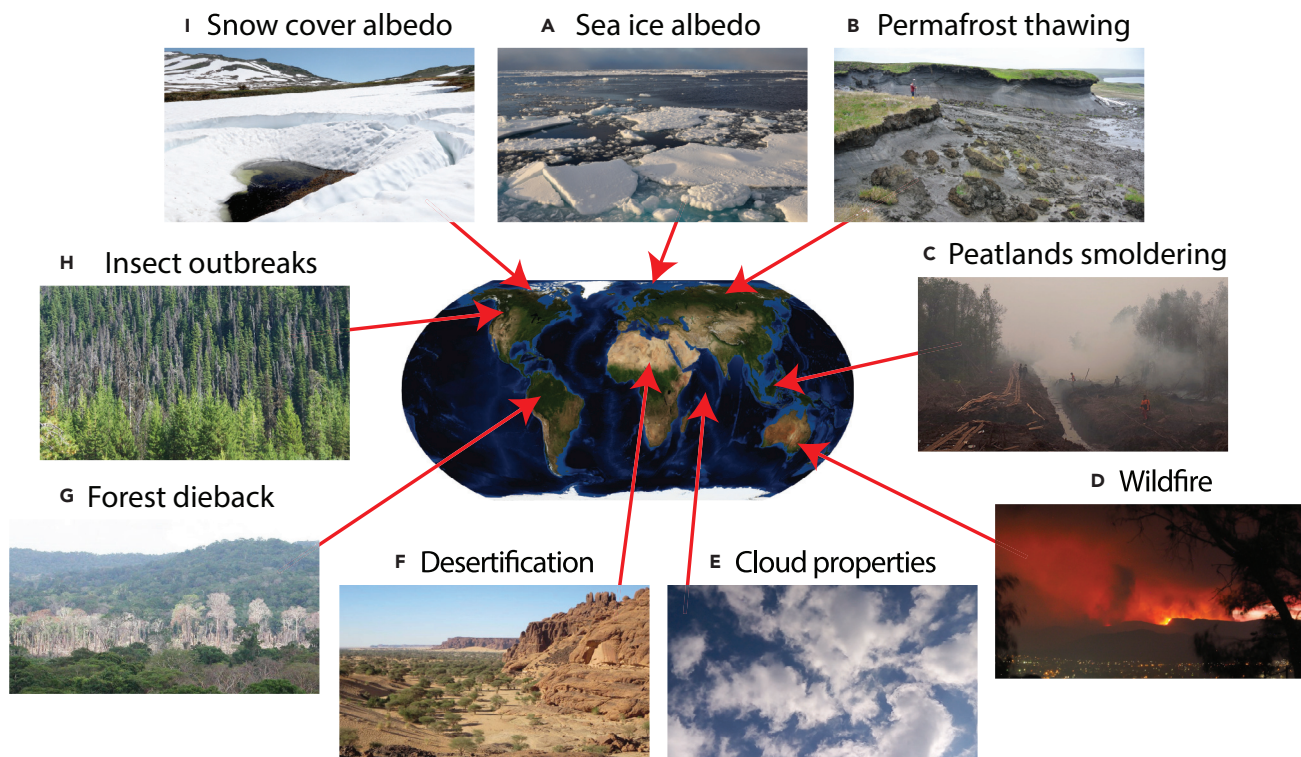


Figure 1. Map of feedback loops

(A–I) The map shows example locations where select positive feedback loops are likely operating. The full extent of the area and locations impacted by each feedback loop are not depicted. Feedback loop summaries: (A) sea ice melting or not forming → decreasing albedo; (B) increasing thawing and decomposition → increasing CO₂ and CH₄ emissions, loss of sequestration; (C) drying and increasing vulnerability to fire/smoldering, decreasing soil organic carbon → increasing release of CO₂ into the atmosphere and decreasing carbon sequestration; (D) increasing fire frequency and/or severity → increasing CO₂ emissions, loss of sequestration, change in albedo; (E) changing cloud distribution and optical properties → altered cloud albedo and greenhouse effect; (F) increasing chronic aridification and hotter drought stress extremes leading to expanding deserts → decreasing CO₂ sequestration, and increasing albedo; (G) dieback of Amazon, boreal, and other forests → loss of sequestration, change in albedo, decreasing evapotranspiration; (H) changing insect distributions and abundances, decreased host tree defense → loss of sequestration, change in albedo; (I) decreasing snow cover → decreasing albedo. See [Table S1](#) for further feedback loop details. Photo credits (also given in [Table S3](#)): (A) Patrick Kelley, CC BY 2.0; (B) Boris Radosavljevic, CC BY 2.0; (C) NASA's Earth Observatory, CC BY 2.0; (D) Nick-D, CC BY-SA 4.0; (E) Doggo19292, Public Domain; (F) David Stanley, CC BY 2.0; (G) NASA/JPL-Caltech, (H) Jonhall, CC BY 3.0, (I) Natalia_Kollegova, Pixabay License.

positive (reinforcing) feedback loops, 7 negative (balancing) feedback loops, and 7 uncertain feedback loops ([Tables 1 and S1](#)). We obtained feedback strengths for 17 of these loops, including 13 strengths in standard units of W/m²/K ([Table S1 and Figure S2](#)). Physical feedback loops involve primarily abiotic systems. For example, warming in the Arctic leads to melting sea ice, which leads to further warming because water has lower albedo (reflectance) than ice ([Figure S3](#)). In contrast, biological loops involve the biosphere in some way. For instance, increasing temperatures lead to permafrost thawing, which produces CO₂ and methane (CH₄) emissions, which in turn leads to further increasing temperatures, and so on ([Figure S3](#)). Note that biological loops can also involve physical components. Because some loops were discovered relatively recently, we

expect additional feedback loops to be described in the near future, especially in the biological category where many complex interactions are possible. Given that most of the feedback loops we identified are positive, it seems likely that many unknown feedbacks are also positive. Collectively, these additional loops could mean that the remaining carbon budget has been overestimated, in which case proposed mitigation pathways may be inadequate and net zero (human) emissions may need to be achieved more quickly than anticipated.⁶ While climate feedbacks, the TCRE, and carbon budgets have been partially constrained using historical and paleo-climate data,⁴ this does not diminish the importance of further research. In particular, we are now seeing greenhouse gas levels that have not occurred in several million years, and we

lack the paleo data to understand carbon-climate and social feedbacks on a much warmer and more carbon-rich planet.⁸

Greenhouse gas emissions have been growing rapidly during the last century, despite several decades of warnings from scientists that emissions must be greatly reduced. Moreover, because climate feedbacks can interact with each other and exhibit temperature dependence^{9,10} and non-linearities, currently weak feedbacks have the potential to become stronger, following warming driven by other feedback loops. In a grim scenario, interacting feedback loops could result in a sequence of climate tipping points being exceeded,^{5,11} producing “climate cascades,” whereby the net effect of reinforcing feedbacks is greater than the sum of their individual effects under current conditions.

Table 1. Summary list of feedback loops

Feedback	Effect of climate change	Effect on climate change	+/-
20 physical feedback loops			
1. Planck [†]	↑ Temperature	↑ Heat loss (radiation)	-
2. Water vapor [†]	↑ Increasing water vapor content	↑ Greenhouse effect	+
3. Sea ice albedo ^{*†}	↑ Sea ice melting or not forming	↓ Albedo	+
4. Ice sheets ^{*†‡}	↑ Glacier & ice sheet melting/instability	↓ Albedo	+
5. Sea level rise [‡]	↑ Sea levels	↓ Albedo (↑ coastal submergence)	+
6. Snow cover [†]	↓ Snow cover	↓ Albedo	+
7. Clouds [†]	Δ Cloud distribution & optical properties	Δ Cloud albedo & greenhouse effect	+
8. Dust [†]	Δ Dust aerosol abundance	Δ Albedo & greenhouse effect	?
9. Other aerosols [†]	Δ Atmos. aerosol conc.	Δ Albedo & greenhouse effect	?
10. Ocean stratification	↑ Ocean stratification	↓ Carbon uptake by ocean	+
11. Ocean circ.*	↓ Ocean circ.	Δ Surface temperature	?
12. Solubility pump [†]	↑ Atmos. CO ₂ levels	↓ CO ₂ absorption by ocean	+
13. CH ₄ hydrates ^{*†‡}	↑ CH ₄ hydrate dissociation rates	↑ Release of CH ₄ into atmos.	+
14. Lapse rate [†]	Δ Temp.-altitude relationships	↓ Global mean temperature	-
15. Ice-elevation [‡]	↓ Ice sheet/glacier elevation	↑ Glacier & ice sheet melting, ↓ albedo	+
16. Antarctic rainfall [‡]	↓ Ice sheet extent, ↑ precipitation	↓ Albedo, ↑ deep ocean warming	+
17. Sea ice growth	↓ Sea ice thickness, ↓ insulation	↑ Thin ice growth rate	-
18. Ozone [†]	Δ Atmos. circ.	↓ Tropical lower stratospheric ozone	?
19. Atmos. reactions [†]	Δ Atmos. chem. reaction rates	Δ Greenhouse effect	?
20. Chem. weathering [‡]	↑ Chemical weathering rates	↑ CO ₂ taken out of atmosphere	-
21 biological feedback loops			
21. Peatlands [†]	↑ Drying and fire, ↓ Soil carbon	↑ Release of CO ₂ into atmos.	+
22. Wetlands [†]	↑ Wetlands area (↑ precipitation)	↑ CO ₂ seq., ↑ CH ₄ emissions	+
23. Freshwater	↑ Aquatic plant growth rates	↑ CH ₄ emissions	+
24. Forest dieback*	↑ Amazon and other forest dieback	↓ CO ₂ seq., Δ albedo	+
25. Northern greening	↑ Boreal forest area, Arctic vegetation	↑ CO ₂ seq., ↓ albedo	+
26. Insects	Δ Insect ranges and abundances	↓ CO ₂ seq., Δ albedo	+
27. Wildfire [†]	↑ Fire activity in some regions	↑ CO ₂ emissions, Δ albedo	+
28. BVOCs [†]	Δ BVOC emission rates	↓ Greenhouse effect, ↑ tropospheric O ₃	-
29. Soil carbon (other)	↑ Loss of soil carbon	↑ CO ₂ emissions	+
30. Soil nitrous oxide [†]	Δ Soil microbial activity	↑ Nitrous oxide emissions	+
31. Permafrost ^{*†}	↑ Permafrost thawing	↑ CO ₂ and CH ₄ emissions	+
32. Soil and plant ET	↑ ET from soils and plants	↓ Latent heat flux	+
33. Microbes (other)	↑ Microbial respiration rates	↑ CO ₂ and CH ₄ emissions	+
34. Plant stress	↑ Thermal stress, ↑ droughts	↑ Plant mortality, ↓ CO ₂ seq.	+
35. Desertification	↑ Desert area	↓ CO ₂ seq., Δ albedo	+
36. Sahara/Sahel greening*	↑ Rainfall in Sahara and Sahel	↑ CO ₂ seq. by vegetation	-
37. CO ₂ fertilization	↑ CO ₂ conc., ↑ NPP	↑ Carbon uptake by vegetation	-
38. Coastal productivity	↑ Coastal ecosystem degradation	↓ Coastal ecosystem carbon seq.	+

(Continued on next page)

Table 1. Continued

Feedback	Effect of climate change	Effect on climate change	+/-
39. Metabolic rates	↑ Phytoplankton respiration rates	↑ CO ₂ released into atmos.	+
40. Ocean bio.	↑ Ocean CO ₂ , ↑ acidification, ↑ temp.	Δ Ocean carbon sink	?
41. Phytoplankton-DMS [†]	Δ Plankton DMS emissions	Δ Cloud albedo	?

Loops are divided into two categories: physical (loop numbers 1–20) and biological (loop numbers 21–41). The rightmost column shows the loop direction (“+”: reinforcing, “-”: balancing, “?”: uncertain). Feedback loops that involve potential tipping elements are marked with asterisks (*; see [supplemental experimental procedures](#)). As a rough indicator of feedbacks that are more likely to be at least partly included in some climate models, loops that are covered in Figure TS.17 (feedbacks overview) or 5.29 (biogeochemical feedbacks) of IPCC⁴ are marked with daggers (†). Many of these feedbacks will have significant effects on Earth’s climate, but others are more speculative and possibly negligible. Feedback impacts operate on time scales ranging from short (e.g., months/years) to very long (e.g., millennia); feedbacks we believe to be exceptionally slow are marked with double daggers (‡). Symbols indicate increasing (↑), decreasing (↓), and changing (Δ), and abbreviations correspond to circulation (circ.), concentration (conc.), temperature (temp.), atmospheric (atmos.), chemical (chem.), sequestration (seq.), biogenic volatile organic compounds (BVOCs), ozone (O₃), evapotranspiration (ET), biological pump (bio.), and dimethyl sulfide (DMS). See [supplemental experimental procedures](#) and [Table S1](#) for complete loop descriptions, grouping order, limitations (e.g., overlapping loops and uncertain tipping elements), and selected references.

Some feedback loops may be associated with key tipping points ([Tables 1 and S1](#)) that could profoundly disrupt the global climate system and biosphere once critical thresholds are crossed. Although it has been argued that most of these tipping points are not expected to drive large positive feedbacks, there is deep uncertainty associated with unlikely but extreme feedbacks and tipping points.⁴ Specific concerns include slowing of ocean circulation and the large-scale loss of ice sheets, permafrost, and forests.² In the worst case, if positive feedbacks are sufficiently strong, this could result in tragic climate change outside the control of humans.⁵

Based on our compilation of numerous and potentially risky climate warming feedback loops, we call for immediate concurrent changes to both (1) climate research and (2) climate policy, which should strategically inform and guide each other.

Climate research

While we applaud the significant accomplishments of feedback researchers to date, we believe an immediate and massive international mobilization must occur to advance climate science with an increase in research priorities and funding to quickly get the impacts and interactions of feedbacks better assessed in the context of the remaining carbon budget. We call for a faster transition toward integrated Earth system science because the climate system can only be understood by integrating the functioning and state of all Earth system interac-

tions.¹² For example, an Earth system science approach can provide information on both mitigation pathways that minimize risks associated with climate feedbacks and the societal transformations needed to pursue these trajectories. This will give policymakers better and more usable scientific information, which is needed to manage risks associated with the climate emergency.

More research is needed to incorporate the mechanisms and processes of diverse feedback loops into climate models, especially biological feedback loops. These have received comparatively little attention and are often grouped together as “unrepresented feedback mechanisms.”^{3,6,13} Therefore, we propose that feedback loops and tipping points as well as their possible combined severe consequences (e.g., potential runaway dynamics) receive more attention, for example, as an IPCC special report. Biological feedback loops involving forest dieback, loss of soil carbon, thawing permafrost, drying and smoldering peatlands, and the changing ocean biological pump are highly uncertain and may be large. Developing a better understanding of these and other feedbacks will require large-scale funding and collaboration to coordinate data collection and synthesis efforts.

As part of an Earth system approach, more research is also needed to identify, quantify, and integrate the myriad of human feedbacks ([Table S2](#)), which is complicated by the inherent uncertainty in the social system.¹⁴ Because they involve complex social and economic systems, it is important that analyses of human feed-

backs be conducted in an interdisciplinary fashion, including researchers from the social sciences in all stages of the process.¹⁵ Overall, insight into the complex trajectories that tie physical, biological, and social feedbacks together may be gained through various methods. Promising approaches include simulations that can reflect the behavior of complex adaptive systems and artificial intelligence-based network analysis of the matrix of feedback loop interactions. Such insights will likely be needed to make progress on two major challenges facing Earth system science: assessing the stability and resiliency of the Earth system and fully integrating biophysical and human dynamics.¹²

Climate policy

Individual countries are not even close to being on track to achieve the Paris emissions reduction pledges that were not enough to meet the insufficient Paris 2.0°C upper limit warming target and are now distressingly inadequate to meet the later 1.5°C warming limit.¹⁶ Worse still, researchers have recently raised the likely minimum equilibrium warming associated with atmospheric CO₂ doubling from 1.5°C (Stocker et al.¹⁷) to a more devastating 2.5°C (IPCC⁴). With these troubling developments in mind, we make two arguments for immediate and massive reductions in emissions. First, we suggest that further small increases in short-term warming are a big risk, considering the suffering that we are already experiencing from climate disasters of “unprecedented” wildfires, intense storms, coastal flooding, permafrost thaw, and extreme

weather that have occurred with just 1.1°C to 1.2°C global average warming. Second, as part of a longer timeline, positive feedback loops and tipping points may pose a major threat. Given the potential for catastrophic climate change and the lack of complete scientific understanding to date, policymakers should strongly consider the potentially dangerous effects of feedback loops, tipping points, and climate cascades, even if all desired scientific data are not available at this time.

Transformative and socially just changes in global energy and transportation, short-lived air pollution, food production, nature preservation, and the international economy, together with population policies based on education and equality, are required to address this immense problem in both the short and the long term.¹ Many of these changes will require significant time, research, and political support to fully carry out. However, reductions in warming due to mitigating methane and other short-lived pollutant emissions can be achieved rapidly. Equitable policies and funding are also needed to support climate adaptations in less wealthy regions where knock-on effects of feedbacks or secondary feedback loop effects are particularly dangerous.

The remaining carbon budget is rapidly shrinking and waiting until 2050 to achieve net-zero carbon emissions might be far too late.¹³ The gap between projected emissions (assuming 2030 mitigation pledges are met) and emissions consistent with 1.5°C is very large, and time is running out to avoid the worst effects of climate change.¹⁶ Specifically, the gap is roughly 23 Gt CO₂e per year in 2030 for 1.5°C.¹⁶ Therefore, shortened timelines for carbon neutrality (before 2050), and more ambitious emissions drawdown with near-term requirements should be swiftly implemented as a response to this emissions gap. Large natural carbon sinks are also critical, but they must be established strategically with relevant biological feedback loops in mind.

Summary

The first step in curbing the near-term climate impacts and minimizing the risk of an eventual catastrophic outcome is for us to expand our awareness of the severity of our predicament.¹⁸ Thus, we

have described an extensive set of potentially harmful feedback loops to increase our understanding, justify a more serious response, and motivate work into less probable but dangerously underexplored scenarios.¹⁸

It is too late to fully prevent the pain of climate change as severe impacts are already being felt, but if we can have a much better understanding of feedback loops and make the needed transformative changes soon while prioritizing basic human needs, there might still be time to limit the harm. Even if it turns out that feedbacks are already sufficiently characterized, these changes will provide enormous benefits to human well-being and the entire biosphere. Conversely, if the worst-case risks posed by feedback loops and tipping points have been underestimated, the future of a hospitable planet Earth may be at stake.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests should be directed to and will be fulfilled by the co-lead contacts, Christopher Wolf (wolfch@oregonstate.edu) and William Ripple (bill.ripple@oregonstate.edu).

Materials availability

This study did not generate new unique materials.

Data and code availability

All data associated with the paper are provided in the Supplemental Information. This paper does not report original code.

Summary of experimental procedures

Here, we provide a summary of the experimental procedures used to construct the tables of feedback loops (Table 1 and S1). Please see the Supplemental Experimental Procedure section for more detail, including limitations.

We compiled an initial set of climate feedback loops by performing a literature review using computerized searches. We considered standard research articles and also review papers dealing with feedback loops. We also examined references cited by these papers.

We grouped the feedback loops into three general categories: Physical (abiotic), Biological, and Human, and we identified feedback loop “types,” which correspond to subcategories.

Because of the complexity of social systems, the human feedback loops may be speculative in nature and difficult to quantify. So, we present these possible feedback loops separately from the physical and biological loops. These human loops are intended as examples only, and this list is not intended to be exhaustive.

We only considered feedbacks to global temperature, excluding internal feedbacks. For each climate feedback loop, we identified two processes: the “effect of climate change” and the “effect on climate change.” For example, warming in the Arctic causes ice to melt (effect of climate change) and melting ice in turn leads to further

warming by decreasing albedo (effect on climate change). We also categorized each loop as positive, negative, or uncertain direction. Lastly, we determined estimates of feedback loop strengths where possible. Feedback strengths are quantified in a number of ways, although units of W/m²/K are standard. When available, we included uncertainty estimates associated with strengths (e.g., standard errors).

Although each feedback loop differs from the others in either the “effect of climate change,” or the “effect on climate change,” there may be overlaps among some groups of feedback loops. Given that these feedback loops can involve many complex and interacting systems, we viewed some degree of overlap as unavoidable. We used footnotes to indicate occurrences of partial overlap (see Table S1). The strength estimates are generally separate and additive, except in cases of overlapping feedback loops. In our feedback loops tables, we included loops that vary in strength over time, many of which could eventually weaken. Likely examples include permafrost (limited capacity to emit greenhouse gases), sea ice (eventually, there may be no sea ice), and forest dieback (eventually, large forested areas could be fully converted to other ecosystem types, possibly halting this process).

The focus of our table is on feedback loops. However, climate tipping elements and tipping points are related concepts that are of major importance to the Earth system. Therefore, we identified the feedback loops in our table that might involve tipping elements.

After constructing the preliminary tables of feedback loops, we then had them reviewed by more than twenty climate feedback experts (see main paper acknowledgments section). These experts were typically authors of feedback loop papers that we cited. We invited them to propose modifications to our tables of feedback loops, such as adding or removing loops, improving loop descriptions, or proposing additional references to cite.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.oneear.2023.01.004>.

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