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Building a carbon dioxide removal science–policy partnership for southern Africa

Significance:

Carbon dioxide removal (CDR) negative emissions interventions are needed to steer the planet to a safe climate by the end of the century. In this Commentary, we frame the rationale and likely challenges for a regionally focused and coordinated CDR-centred science–policy platform with a global reach to support the opportunities and minimise the risks associated with CDR in southern Africa. We make a first attempt to frame a new CDR-centred strategic compact in the science–government–innovation–business nexus that is required to enable South Africa to provide regional and global climate leadership and impact over the 21st century.

All IPCC emission scenarios that aim to avoid dangerous climate change require carbon dioxide removal (CDR) negative emissions interventions to steer the planet to a safe climate by the end of the century.[1-5] Effective negative CO_2 emissions will be required on a scale that matches the order of magnitude of present positive emissions from oil, gas and coal.[4-6] For South Africa, this translates to CDR interventions in the order of 0.1–0.5 Gigatons of CO_2 per year ($GtCO_2$/year), which at the present carbon price range of USD100 per ton of CO_2 would equate to an annual USD10–50 B/year industry, excluding the required infrastructure and skills investments and avoided costs of climate damage.[7] CDR is thus a key element of South Africa's emerging economic development strategy, re-shaping science, mitigation, adaptation and financing policies and investments to strengthen the transition towards and beyond net-zero.[8,9] However, there are as yet very limited relevant governance mechanisms in place, technologies are in their infancy, and the scientific and tertiary training capabilities are largely unprepared to support these developments.[10] CDR represents a significant innovation, development and educational opportunity, but only if academic, science and policy (public and business) communities can build consensus on the efficacy and prioritisation of regionally suited selected approaches and coordinate efforts around this key regional–global challenge to avoid dangerous climate change.[9-11]

What is CDR?

Carbon dioxide removal (CDR) comprises a variety of anthropogenic interventions that, directly or indirectly, **remove CO_2 from the atmosphere and store it durably** in geological, terrestrial, or ocean reservoirs, or in long-life products[3] (Figure 1). CDR is not carbon dioxide reduction, or emissions reductions, which is needed to achieve the policy goal of net-zero emissions.[3] CDR interventions can range from ecosystem process enhancements on land and in the ocean, through enhanced geochemical cycles to technology-intensive interventions such as direct air capture[2,3,5,6] (Figure 1). All these interventions aim to sequester and store the CO_2 removed from the atmosphere for the long term (>10 K years) in appropriate terrestrial and ocean reservoirs (Figure 1).[3,5,6] Thus CDR is a system of interventions and feedbacks, which determine its efficacy. Its integrated totality involves not just the interventions and their ecosystem trade-offs, but also the planetary–regional carbon-concentration and carbon-climate feedbacks in both land and ocean carbon sinks (Figure 1). It is the integrated nature of the entire CDR 'system', including the feedbacks, that determines the efficacy and 'final' magnitudes of CDR interventions.[3,6]

There are four main sources of risk and uncertainty that influence the efficacy and scalability of CDR. Firstly, there are economic, human livelihood, and biodiversity trade-offs directly or indirectly linked to the interventions; for example, interventions in land (includes agriculture) and ocean ecosystem processes, additional natural resource requirements and far-field unanticipated impacts.[3,5,6,11-14] These trade-offs are to a large extent within current – policies and scientific capabilities. Secondly, there are societal and science concerns about the ideas of further intervention in the climate system, which is where the as-yet underdeveloped CDR governance policy is critical to building trust and confidence through greater transparency.[10] Thirdly, there are significant knowledge gaps relating to the response of carbon-climate (heat) feedbacks from the ocean and land reservoirs to the interventions, as well as on and the nature and trajectories of the reversibility of climate change impacts on land and in the ocean (Figure 1).[5,6,12,14,15] These are projected to have the biggest influence on the uncertainty of CDR efficacy, which will impact society through carbon pricing, management of climate risk, and the costs of adaptation and mitigation. Finally, there are risks related to the as-yet uncertain feasibility and scalability of the technological interventions, such as direct air capture of CO_2, biomass energy with carbon capture (BECCS), and geochemical-, biogeochemical- and nature-based enhancements of the carbon cycle.[10,13]

CDR is likely to emerge and grow in two main phases. In the short term (±10–30 years), CDR is urgently needed to support the global policy aim of achieving net-zero emissions for greenhouse gases by 2050, especially in the context of an increasingly likely short-term temperature target overshoot emissions scenario.[4] During this initial period, the global response needs to accommodate not only slower emissions reduction trajectories in some countries, but also the weakly constrained but likely countervailing effects of improving air quality on radiative forcing, non-CO_2 emissions trajectories (CH_4 and N_2O), and recalcitrance in sectors with hard-to-abate emissions, such as air travel.[13] In South Africa, this may involve the integration of CDR into emissions reduction policies such as the Long Term Mitigation Strategy, its nationally determined contributions and its contribution to the global stocktake, also with the aim of meeting the policy objective of net-zero emissions by 2050.[8] However, this also raises the jeopardy of CDR being used to offset rather than complement emissions reductions, which

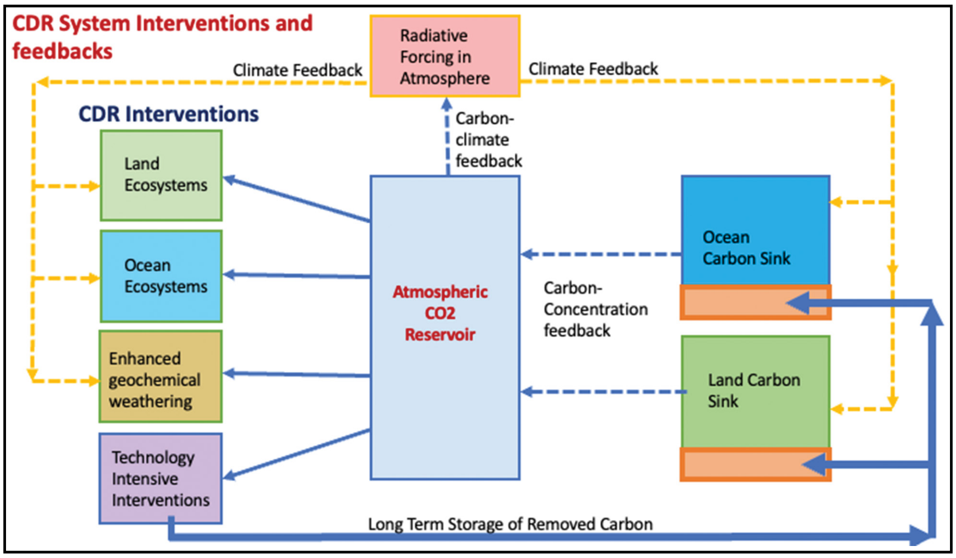


Figure 1: Schematic of the integrated key intervention–feedback nexus elements of a carbon dioxide removal (CDR) system. The main CDR intervention categories draw down atmospheric CO_2 (solid blue arrows) and store it in long-term land and ocean reservoirs (solid bold blue arrows). The active land and ocean reservoirs modulate the carbon-concentration feedback (dashed blue arrows), which sets the net decrease in atmospheric CO_2 and radiative forcing. Hence the effectiveness of the CDR interventions on the carbon-climate (heat and water) feedbacks in both the land and ocean ecosystems on both the intervention and response sides (dashed orange arrows). See Figure 3 for specific categories.

again highlights the urgency of well-founded science–governance policy capabilities.[9-11] In the medium to long term (20–100 years), CDR's growing and most likely largest impact will be to address the warming commitment from historical emissions, which remains a challenge to reducing global radiative forcing down to 1.9 W/m² or 2.6 W/m² by 2100 to meet 1.5 °C and 2 °C targets, respectively.[2,3,16] The existential challenges to achieving these objectives at the global scale imply an urgent need to build and coordinate the required science, technological and policy capacity at all regional and global levels.

Global-scale science challenges

Initial global-scale modelling results highlight substantive science challenges that have a bearing on the effectiveness of CDR.[2,3,6,16-18] The re-balancing of the land and ocean carbon and energy reservoirs under CDR are poorly constrained at the global and regional levels, and the dynamics of the regional ocean and land systems feedback contributions to the mean global response are uncertain.[3,6] Perhaps the biggest challenges are in the asymmetry of the contrasting quasi-linearity and non-linearity of the relationship between temperature change and cumulative emissions under positive and negative emissions, respectively (Figure 2a).[17,18] The response of surface air temperature to CDR-driven negative emissions does not mirror changes from positive emissions.[17,18]

Under positive emissions, the relationship between cumulative CO_2 emissions and temperature change, the Transient Climate Response to cumulative carbon Emissions (TCRE), is quasi-linear and path independent (Figure 2a).[3] This enables TCRE to be used to calculate one of the most policy relevant and socially transforming planetary metrics in support of mitigation policy: the remaining carbon budget.[3] In sharp contrast, the non-linearity of TCRE, and its hysteresis under negative emissions (n-TCRE), arises mainly from the lags in the response of ocean fluxes of CO_2 and heat across the base of the ocean mixed layer as well as the divergent responses of net ocean heat and CO_2 fluxes to negative emissions arising from the orthogonal profiles of temperature and CO_2 in the ocean.[3,17,18] On land, the non-linearities may arise from the slow rates of ecological adjustments, such as from shifts in dominant plant photosynthetic and structural types (biomes) that will occur in response to decreasing atmospheric CO_2.[3,16] One of the main practical outcomes from this non-linearity is that CDR is likely not as effective at cooling as positive CO_2 emissions are at warming[3] – a potentially significant policy and societal planning and trust challenge.

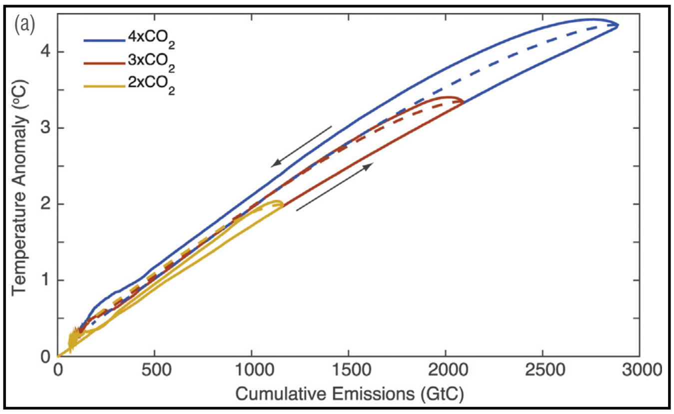
The second possible outcome impacting the effectiveness of CDR is the re-balancing of the anthropogenic CO_2 stored in ocean and land sinks during the historical positive emissions period (Figure 2b).[3] Idealised model experiments suggest that about 40–60% of the total CO_2 removed from the atmosphere by CDR would be counterbalanced by outgassing from both the contemporary ocean and land sinks (Figure 2b). The question arises: how sensitive are these rates and magnitudes of re-balancing to the scales at which the models capture regional specificities in the physics and biogeochemistry? These could include heterogeneous carbon sinks in soils, dissolved terrestrially fixed carbon exported into the ocean, carbon sinks accumulated on the ocean floor, ocean stratification, upwelling and lateral ocean current transport. There is currently almost no work underway to project and experimentally constrain these processes.

The projected confidence levels for the biogeochemical impacts of CDR are synthesised and assessed in Figure 3, which links the projected temporal effectiveness and scalability of the main intervention types to the confidence and direction of the earth system feedbacks, and ecosystem-scale biogeochemical and biophysical effects and co-benefits.[3] The key point of this global assessment is the widespread low confidence in the impacts and their direction (Figure 3).

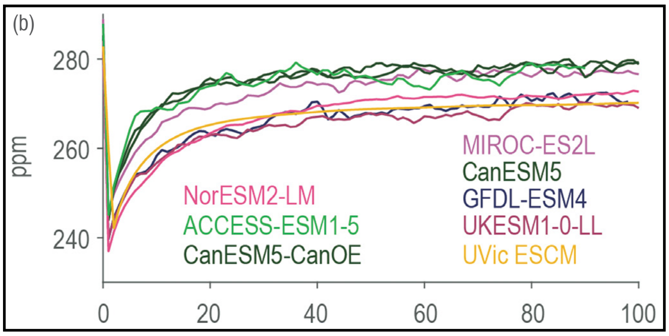
The question then arises: could a regional-scale approach help address these global sources of uncertainty in respect of land and ocean CDR? How coupled regional land–ocean–atmosphere processes contribute to the global impact of CDR through both the carbon and heat fluxes is one of the most pressing science challenges. Can a regional focus with higher temporal and spatial resolution of the process variability strengthen confidence in the assessment of CDR effectiveness? How might natural ocean and terrestrial processes, particularly in the Southern African Regional Earth System (SA-RES), be enhanced to contribute more to the global effectiveness of CDR? This creates an opportunity for South African science to use its comparative regional geographical, climate and ecological advantages to both regional and global benefit.

Why a regional focus? Addressing the feedback scale challenges

The processes that influence the outcomes of CDR interventions comprise a very wide range of spatial (from one to thousands of kilometres) and temporal (days to decades) scales of variability on



Source: Zickfeld et al.[17] under licence CC-BY 3.0



Source: Canadell et al.[3] with permission (©IPCC)

Figure 2: Two idealised modelling experiment responses of the global carbon-climate system which have a major influence on the effectiveness of carbon dioxide removal (CDR): (a) the quasi-linear response of warming to increasing cumulative positive emissions contrasted with the non-linear response of cooling to negative cumulative emissions, and (b) the rapid (<20 years) re-balancing of atmospheric CO_2 by the land and ocean carbon reservoirs, which is projected to reduce the effectiveness of CDR by 40–60%.[3,17]

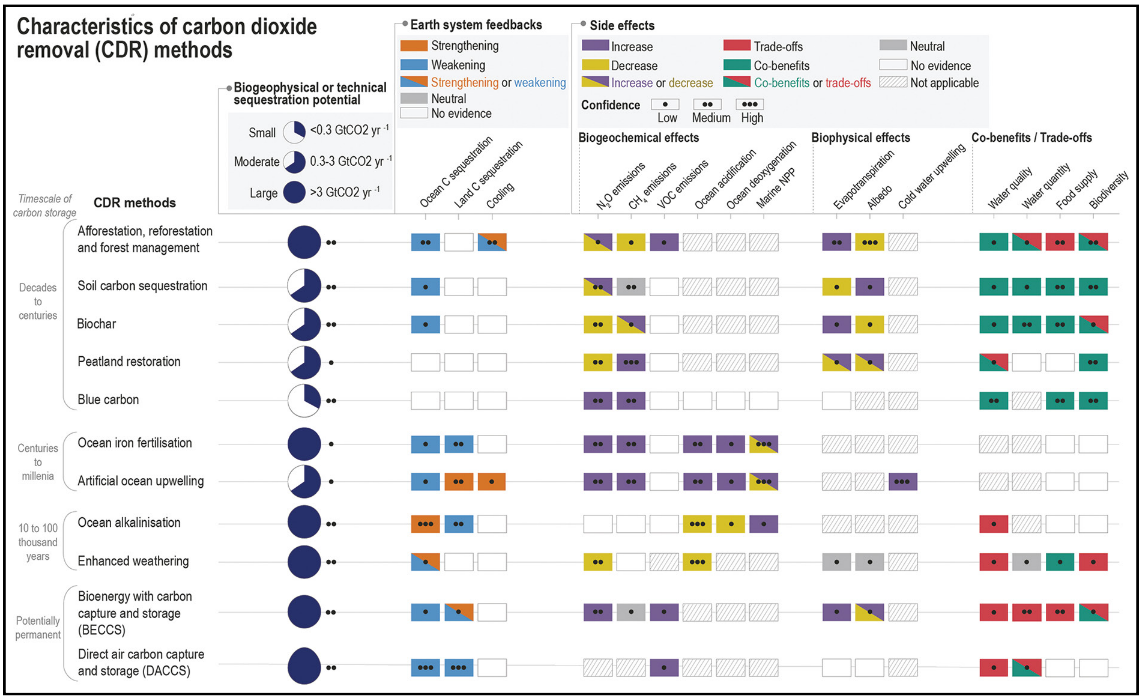


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Figure 3: Global synthesis assessment of the scalability, earth system feedbacks, biogeochemical effects and co-benefits of carbon dioxide removal (CDR) interventions. This figure highlights the major science and policy challenges regarding both the scalability as well as the low confidence levels in respect of the magnitude and direction of the responses.[3]

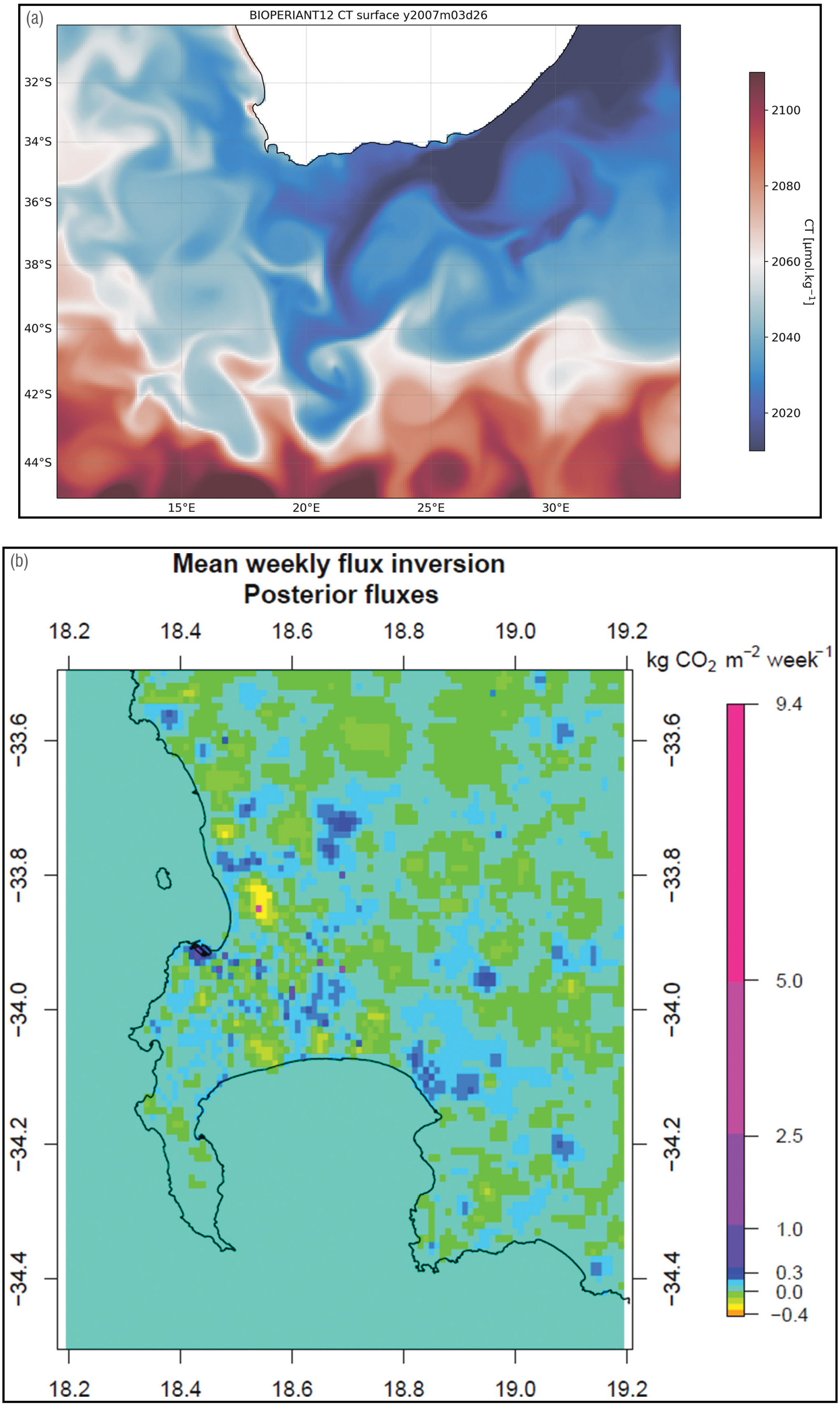

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Figure 4: The importance and the challenge of fine spatial scales in SA-RES. (a) A high-resolution model reconstruction of the influence of eddies (±10–100 km) and circulation dynamics on the CO_2 gradients in the regional ocean: the warm and low CO_2 Agulhas system in the east, the cool and high CO_2 Benguela upwelling system in the west and the high CO_2 boundary with the Southern Ocean in the south. (b) An inversion model reconstruction of land carbon fluxes in the Western Cape showing the important fine scale (±1–10 km) of the spatial variability in the natural, agricultural, urban and industrial domains of the system[24] (Chang N 2023 January, personal communication).

land and in the ocean. These are critical to understand and project the links and feedbacks between human interventions and the response of natural systems. The integration across these scales presents major modelling and observational challenges, which are well established for positive emissions.[19] In order for global earth system models to run very long projections they need to be set up at medium to low resolutions (25–100 km) that do not capture the spatial and temporal scales critical to the sensitivity to perturbations of the processes.[19] Global model projections at higher resolution are still computationally expensive. The uncoupling of heat and carbon fluxes from the ocean and the slow ecological response of land carbon reservoirs under negative emissions makes it, we suggest, necessary to resolve the finer scales of global earth system models. This, we propose, as a priority towards achieving higher confidence in the projections of non-linear responses that influence the efficacy of CDR. These have profound implications for the resolution choices for models used in projections as well as observations used to evaluate the confidence in those projections. It also presents challenges to integrated assessment models used to understand the sensitivities of the societal–natural systems feedbacks that are critical to the efficacy and scalability and economic outcomes from CDR.

Here we propose that the regional carbon-climate ecosystem science community address this challenge through a dual-linked regional–global observational and modelling approach. There are a number of critical questions: Can a regional focus for the coupled natural–human systems strengthen the global CDR effectiveness and scalability governance policies? Global earth system models implicitly include regional processes and their feedback characteristics on land and in the ocean, so why is there a need for a regional focus?

The proposed Southern African Regional Earth System (SA-RES) with its linked land and ocean ecosystems has unique and highly energetic carbon-climate, biogeochemical and ecological sensitivities and feedbacks that need to be adequately understood.[14,20-23] Studies have highlighted the spatially heterogeneous nature of land and ocean systems, which could influence the effectiveness of CDR interventions (Figure 4a,b).[21,23,24] This is well reflected in the gradients of dissolved CO_2 in the ocean (Figure 4a) and the heterogeneous fine-scale gradients of carbon fluxes in the SW Cape (Figure 4b).[24]

Two further aspects of SA-RES that remain particularly weakly constrained are the land–ocean coupling of carbon fluxes from the river basin scale through the estuaries to the coastal and regional ocean as well as the coupling of SA-RES to the Southern Ocean. Recent work on land and the ocean has highlighted that system-scale reconstructions of variability from models and observations are sensitive to small scales of variability in space and time.[20,23,25] These then influence both their suitability for specific interventions and the scaled-up trade-offs, and collectively they define the regional feedbacks, which ultimately set the magnitude of the effectiveness and their net contribution to global negative emissions.

Final comments

The high-level framing question for this Commentary was: is the South African science–policy community ready and capable of assessing the scalability and effectiveness of regional and/or global CDR interventions? IPCC-AR6 assessments highlighted that CDR is now recognised as the critical global carbon lever to achieve a soft landing for climate within this century. CDR is needed to assist in achieving net-zero by mid-century and then, beyond that, to address the zero emissions commitment from embedded warming from historical emissions. While CDR acts on global warming and climate change through its impact on the global airborne fraction of anthropogenic CO_2 (Figure 1), the technological interventions and the resulting feedbacks are likely to be very scale sensitive and regionally differentiated in character. Understanding and projecting the global-scale feedbacks is considered critical to reliably projecting the scalability and effectiveness of CDR and its developmental co-benefits.

Even if ecological and technological interventions were ready and operational at scale, the science is still weak (low confidence) for the land and ocean feedbacks that are likely to have a first-order impact on the evaluation of the effectiveness of regional and global CDR (Figure 1). A regional focus, that builds on South Africa's comparative geographical advantage and catalyses Africa's climate science–mitigation–adaptation nexus is thus proposed as necessary in order to overcome this CDR challenge (Figure 5). This requires an (as-yet non-existent) regional integration of observational and modelling capabilities (Figure 5). The hub science-to-society integration is proposed to be accomplished through a regionally adapted integrated assessment model (SA-IAM). This aims to enable a quantitative examination of the assumptions and trade-offs across the science–society boundary for the coupled human–earth system. The individual capabilities for this already exist and are increasingly better understood by South African scientists and their broader networks (Figure 5). However, these functionalities need to be further developed and coordinated across most national science and policy institutions in support of increasing development choices through skills and avoiding costly errors.

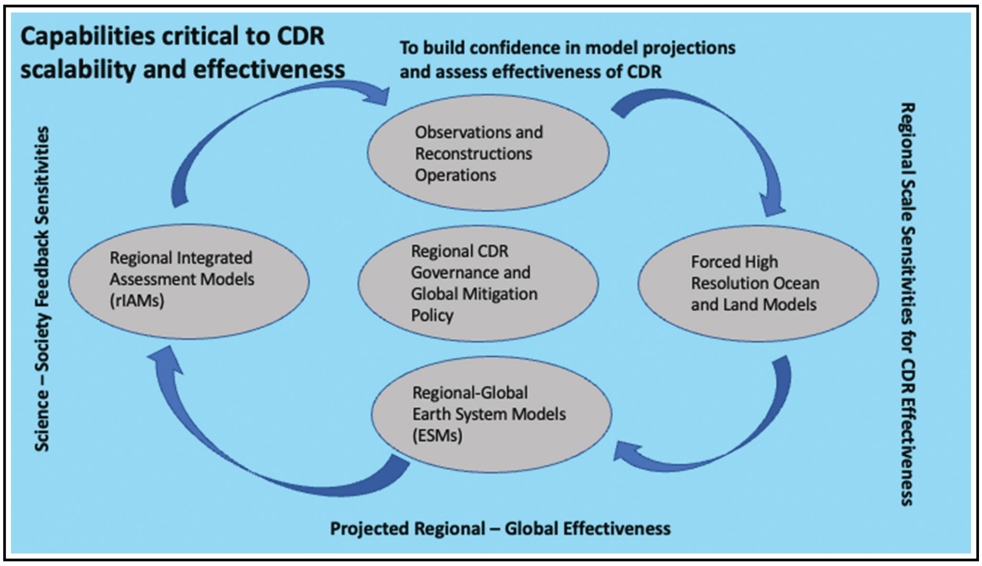

Figure 5: A schematic that sets out the proposed value chain of core science–society capabilities critical to a regional carbon dioxide removal (CDR) Science–Policy Hub. A regionally adapted integrated assessment model (IAM) is the platform that links the science to societal needs and investment requirements. The IAM is supported by optimised observing systems to evaluate the effectiveness of regional and global CDR, high-resolution models to evaluate the local trade-offs of interventions, and the earth system models (ESMs) to provide the projections for the effectiveness of CDR.

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Competing interests

We have no competing interests to declare.

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