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Powers of 10: seeking 'sweet spots' for rapid climate and sustainability actions between individual and global scales

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Abstract

Achieving the goals of the Paris Agreement and related sustainability initiatives will require halving of global greenhouse gas emissions each decade from now on through to 2050, when net zero emissions should be achieved. To reach such significant reductions requires a rapid and strategic scaling of existing and emerging technologies and practices, coupled with economic and social transformations and novel governance solutions. Here we present a new 'Powers of 10' (P10) logarithmic framework and demonstrate its potential as a practical tool for decision makers and change agents at multiple scales to inform and catalyze engagement and actions, complementing and adding nuance to existing frameworks. P10 assists in identifying the suitable cohorts and cohort ranges for rapidly deploying climate and sustainability actions between a single individual and the globally projected ∼ 10 billion persons by 2050. Applying a robust dataset of climate solutions from Project Drawdown's Plausible scenario that could cumulatively reduce greenhouse gas emissions by 1051 gigatons (Gt) against a reference scenario (2190 Gt) between 2020 and 2050, we seek to identify a 'sweet spot' where these climate and sustainability actions are suitably scaled. We suggest that prioritizing the analyzed climate actions between community and urban scales, where global and local converge, can help catalyze and enhance individual, household and local practices, and support national and international policies and finances for rapid sustainability transformations.

1. Introduction

While there is almost unanimous international agreement to the aspirational goals of rapid reduction of greenhouse gases set forth in the Paris Agreement (UNFCCC 2017b) and related initiatives such as the Sustainable Development Goals (SDGs) (UNGA 2015), the ability to translate these aspirations into reality is challenged by the need to effectively scale existing actions and quickly design, test and deploy emerging ones (Ostrom 2010, Hale 2016). However, plans for deploying multi-scale climate actions frequently rely on relative and subjective terms such

as 'national', 'state', 'regional', 'community', and 'local' to frame the populations involved (Ostrom 2010). Usage of such terminology lacks the precision necessary for identifying the scale (state, sub-, nonstate or individual) for forming 'agency', which we define as the capacity of change agents to make decisions, influence actors and take actions, and also implement and benefit from the actions first hand (details in materials and methods). Such agency, involving individual, collective and often proxy efficacy (Bandura 2006), is fundamental to deploy actions leading to greenhouse gas reduction, adaptive technologies and strategies, and enhanced quality of family and community life (Wilson 2012, Hsu *et al* 2019). Additionally, some scales may be more important for effective climate

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and sustainability actions than others (Wilson 2012, Roelfsema *et al* 2018) and to overcome 'fractal carbon traps' and other obstacles that impede rapid progress (Bernstein and Hoffmann 2019).

Since the signing of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, efforts to address global warming and climate change have primarily focused on top-down, national government initiatives and agents, i.e. Nationally Determined Contributions (NDCs) (Wilson 2012, UNFCCC 2017a). Yet among the 193 United Nations member states, with their 'common but differentiated responsibilities,' there is a range of more than four magnitudes in population size (Alesina 2003) (details in supplementary table S1) (available online at stacks.iop.org/ERL/15/094011/mmedia). Focusing on nation state actors without emphasizing their variable populations obscures the fact that the 40 megacities with over 10 million inhabitants have a combined population of over 700 million, more than double the total of the nations at or below the median (supplementary table S1). The Paris Agreement marked a shift away from rules-based governance towards goals-based governance, requiring innovative approaches to engage multiple agents and sectors of society (Hale 2016, Hsu *et al* 2017, UNFCCC 2017b, Tàbara *et al* 2018). However, well before the Paris Agreement, there have been scores of efforts to mobilize climate actions and support sustainable practices in subnational and nongovernmental entities (Landauer *et al* 2018, Nagendra 2018, Lam *et al* 2020). Over the last two decades, as many universities, municipalities, counties, states and corporations began to develop their own climate action plans or strategies, alliances and collaboratives have emerged, including the U.S. Climate Alliance and C40.org, all operating at varying, sometimes overlapping scales. Efforts to promote bottom-up climate actions through individual and household behavior changes and consumer choices have also been proposed, which often take the form of 'the top ten things you can do to stop global warming' such as becoming vegetarian and flying less often (Geels *et al* 2017). As the field for global warming intervention broadens to recognize the range of subnational efforts, the available metrics for scaling and measuring progress of climate actions are often misleading (Ostrom 2010, Wilson 2012, Hsu *et al* 2019). While existing hierarchical societal frameworks are important tools for understanding structural dynamics (Ostrom 2010, Landauer *et al* 2018, Nagendra 2018), there has been no accessible framework to methodically examine, measure and track the success of climate actions at scale (Hsu *et al* 2017, 2019).

In the case of other sustainability challenges, for example, the ongoing contagion of the acute respiratory syndrome coronavirus 2 (SARS-CoV-2), there are many complex levels of governance, and mitigation and adaptation measures between the international global response, currently led by the World Health Organization (WHO), and the single individual who may or may not abide by the guidance or restrictions issued at the international, national, states, regional, municipal or institutional level (WHO 2020). While a range of actions recommended for individuals and households by experts, such as washing hands and avoiding touching one's face, full quarantine or lockdown in particular regions or entire countries have been imposed and then lifted by some nation states and other similar governance entities. However, some of the most successful measures to contain the SARS-CoV-2 pandemic were orchestrated at the community level through honest reporting, co-operation and information sharing, e.g. in South Korea, Taiwan and Singapore (World Health Organization (WHO) 2020). Given the varied responses to SARS-CoV-2 and other sustainability challenges at scale, a framework for optimization (maximized impact through intervention at appropriate scale, see details in materials and methods) of agencies is crucial.

Here we propose the logarithmic 'Powers of 10 (P10)' framework to overcome the relative and subjective bias in the existing approach to climate and sustainability actions and help identify individual, proxy and collective agencies, and corresponding systemic and institutional dynamics and policies across scales (details in figure 1). Using the ten orders of magnitude between a single individual and the projected ~ 10 billion global population by 2050 as a framework for scaling, we propose a method to quantify the 'sweet spot' for forming agency at and between scales. We formalized population cohorts with a preliminary taxonomy (table 1), which is in alignment with and complementary to published research on cross-scale dynamics and hierarchical structures in decision-making (Landauer *et al* 2018).

As addressed in detail in the Intergovernmental Panel on Climate Change (IPCC) 1.5° C emission pathways and formalized as the 'Carbon Law' (Rockström *et al* 2017, IPCC 2018), global greenhouse gas emissions must be cut in half each decade from 2020 until the year 2050 to meet the objective of the Paris Agreement. However, there remains a substantial gap between emissions reduction targeted and actual rate of reduction currently underway (Tàbara *et al* 2018). The unprecedented climate actions required for halving emissions mandates rapid scaling up of adaptation and mitigation measures in all sectors through a combination of climate leadership, technological advancements and social transformations that maximize impact at appropriate scale (Bandura 2006, Otto *et al* 2020). The P10 framework adds value and precision to existing cross-scale frameworks, thereby helping target agency and interventions for climate and sustainability actions by emphasizing transformations at scale (Landauer *et al* 2018).

To demonstrate how the P10 framework could be applied by change agents to discern the suitable

Table 1. Taxonomy and description of the Powers of 10 (P10) cohorts. The proposed taxonomy titles are necessarily relative and imprecise, with the order and degree of magnitude being the key for measuring and optimizing scaling.

Cohort	Population Size	P10 Cohort	Proposed Taxonomy (Name: Entities)
$10°$	One	P0	Individual: each person on the planet
10^1	Ten	P1	Family: couples, households of all types and sizes, close friends, micro-business
10^2	One Hundred	P2	Personal Network: extended family, near neighbors, peers at school/work, small-medium businesses, social network
10^3	One Thousand	P3	Village: rural towns, large urban neighborhoods and schools, colleges, farms
10^4	Ten Thousand	P4	Community: small municipalities, large companies, suburbs, universities
10^5	One Hundred Thousand	P5	Metacommunity: set of interacting communities, mid-sized municipalities, large enterprises
10^6	One Million	P6	Urban/Region: urban areas and cities, workforce of largest multinational entities, regional governments
10^7	Ten Million	P7	Nation/State: megacities, states, nations, bioregions (e.g. Puget Sound)
10^8	One hundred million	P8	Sub-Continental: transnational and sub-continental jurisdictions, entities or areas
10^9	One billion	P9	Continental: continental and multinational entities or areas
10^{10}	Ten Billion	P10	Global: global treaties, agreements and organizations
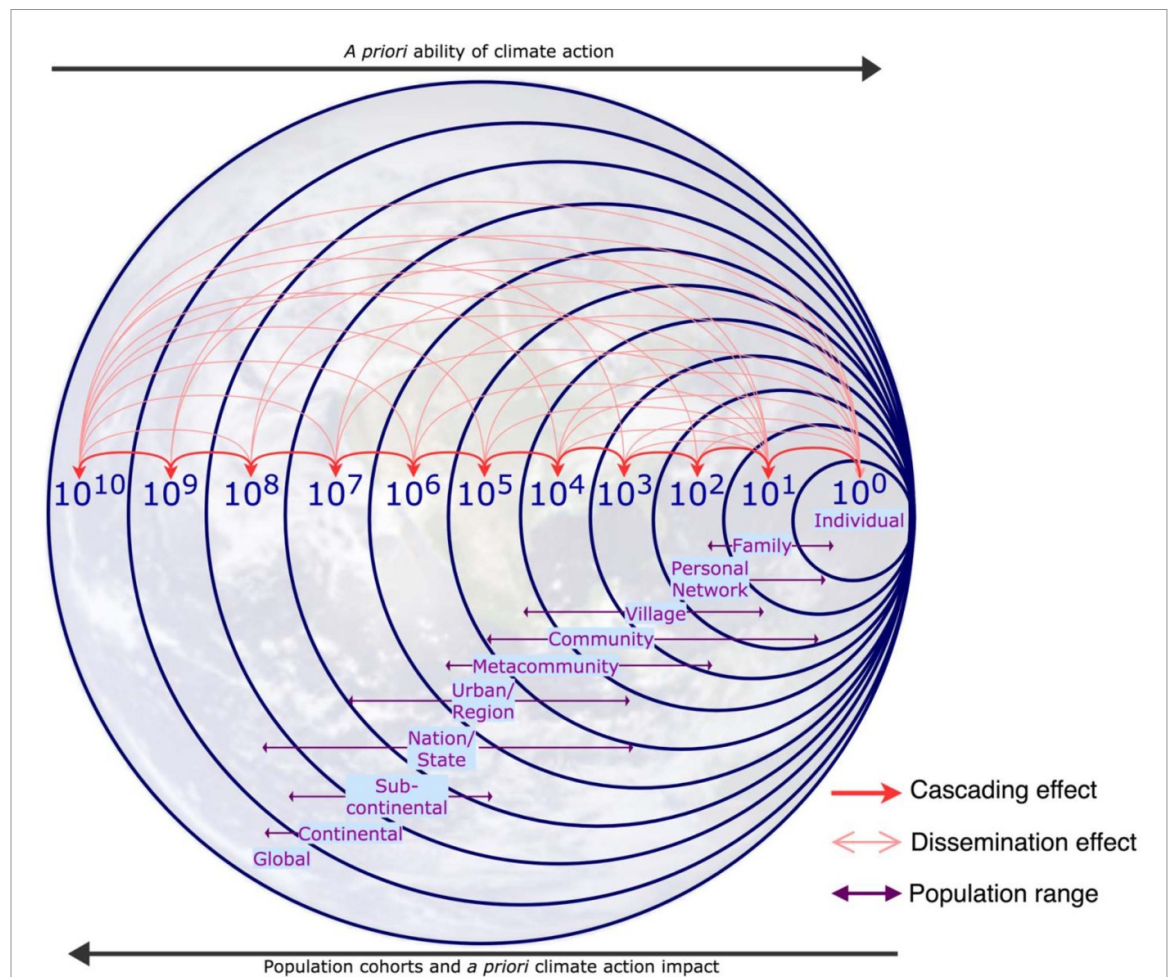
Figure 1. The P10 framework employs exponent scaling (x^n, $x \in N$ and $n = 0$–10) to frame ten orders of magnitude between a single individual and ~ 10 billion persons projected on the planet Earth by 2050. The framework yields 11 population cohorts, i.e. $10°$–10^{10} (P0—P10), in which the projected ~ 10 billion persons are aggregated and distributed irrespective of the relative sizes of nations, communities, schools, and other traditional social institutions that often span several orders of magnitude. A P10 taxonomy analogous to the conventional social-geographic cohorts is proposed (see table 1 for details), of which the median population sizes roughly correspond to respective P10 cohorts (table S1).

scales for the strategic deployment of climate and sustainability actions and the related economic and social policy instruments and technologies that will achieve economic benefits and carbon dioxide equivalent (CO_2e) reductions (Long 2016), we (i) applied a robust dataset from Project Drawdown (PD) 'Plausible scenario' (Hawken 2017), (ii) modeled the potential contribution of each of the cohorts of our P10 framework, and (iii) calculated the net reduction of CO_2e concentrations and the net economic benefit achieved between 2020–2050. We hypothesized that overall there would be a 'sweet spot' for optimizing agency and maximizing impact of climate actions around the median between P0 and P10 cohorts. We also examined whether and how P10 relates to geographic scaling (Wilson 2012, Long 2016) and, as an example of overlap with other cross-scale frameworks, demonstrate P10's synergy with the 'transformation spheres' theory (O'Brien and Sygna 2013) where social transformations are depicted as a process taking place across embedded and interacting personal, political, and practical realms.

2. Materials and methods

2.1. Data
We used the PD climate solutions dataset to demonstrate the potential of the P10 framework and examine possible insights for practical application (Hawken 2017). PD's reference emission scenario (RES) over 2015–2050 was developed using the average global greenhouse gas emissions projections from 11 European Union's Seventh Framework Program (AMPERE) models that adopted the reference policy (RefPol) scenarios assuming frozen global emissions policy over the period 2015–2050 (Kriegler *et al* 2015). The RefPol scenarios were designed to match the non-binding emissions reduction pledges and resulting policies made by several major emitters in the Copenhagen Accord of 2009 (Riahi *et al* 2015). The cumulative Kyoto gas emission for the RES averaged over 11 AMPERE models is 2190 gigatons (Gt) CO_2e between 2020–2050, which was the adjusted RefPol emission by including United Nations population projections for this period to account for the impact of health and education (Hawken 2017).

For the purposes of this analysis, we used the July 2017 dataset relating to the Plausible scenario provided by PD, which examined 76 climate solutions that if effectively deployed between 2020 and 2050 would result in a cumulative reduction of 1051.01 Gt of CO_2e against the RES. The implementation and operation of all solutions in the Plausible scenario between 2020–2050 will result in a cumulative first cost of 135.5 trillion USD, which is 27.4 trillion USD more than the cumulative implementation costs in the RES whereas a cumulative net reduction in operational costs of 73.8 trillion USD compared to the RES. The PD Plausible scenario is roughly in

line with the 'well below 2 °C above pre-industrial levels' goal of the Paris Agreement (UNFCCC 2017b) to frame the scale and timeframe of responding to climate change. Four solutions categories were combined: on and offshore wind turbines, LED lighting household and commercial, improved rice cultivation and system of rice intensification, and large and small methane digesters, for a combined total of 72 climate solutions for our analysis. Details on the PD data and assumptions are provided in the supplementary materials.
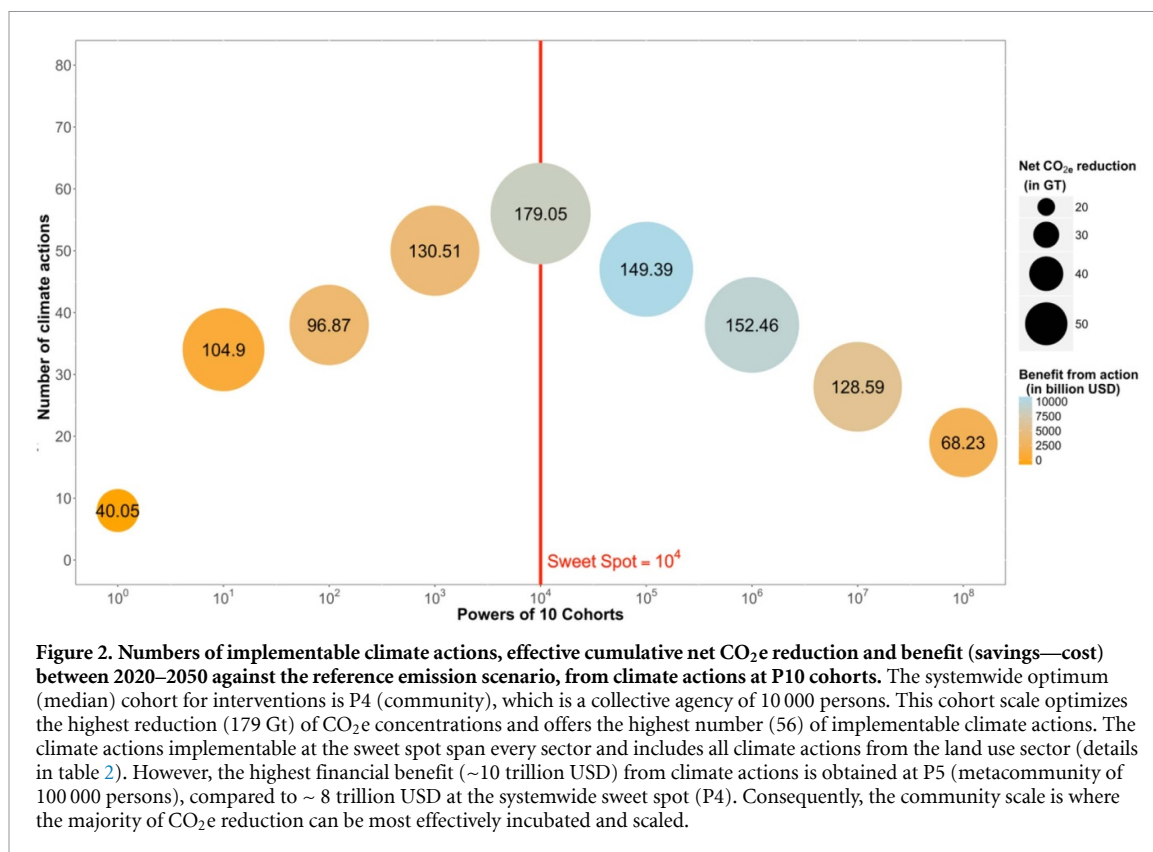
2.2. Identification of suitable P10 cohort ranges
We examined the societal scales that would be suitable (i.e. 'sweet spot') for implementation and benefits for the climate solutions reviewed and modeled by the Plausible scenario in PD. We defined the sweet spot as the range in the number of people (P10 cohorts and cohort ranges), which is suitable to form agency for climate and sustainability actions. Our concept of agency for climate and sustainability actions includes individual, proxy and collective agencies (Archer and Archer 1996, Bandura 2006). Individual agency refers to situations, in which people bring their influence to bear their own functioning. Proxy, or socially mediated agency, refers to situations in which individuals have no direct control over conditions that affect their lives but they influence others who have the resources, knowledge, and means to act on their behalf to secure the outcome they desire. Collective agency refers to situations, in which individuals pool their knowledge, skills, and resources, and act in concert to shape their future (see Bandura (2006) for details).

We used the following criteria for determining suitable cohorts or cohort ranges identification that would form agency for climate and sustainability actions (Bandura 2006, Hawken 2017):

- The number of people within the selected cohort or cohort range has the capability to form agencies for decision making to implement the particular climate solution at hand;
- The number of people within the selected cohort or cohort range will actively engage and implement the climate solution in question first hand through the formed agency; and
- The number of people within the selected cohort or cohort range and the formed agency will benefit or lose first hand economically from implementation of the climate solution in question.

Following the criteria for sweet spot for forming agencies for climate and sustainability actions, we identified the P10 cohorts and cohort ranges suitable for implementation of each of the 72 climate solutions through an iterative process of tagging and reviewing each climate solution. The iteration and identification followed a three-step expert elicitation procedure:

Figure 2. Numbers of implementable climate actions, effective cumulative net CO$_2$e reduction and benefit (savings—cost) between 2020–2050 against the reference emission scenario, from climate actions at P10 cohorts. The systemwide optimum (median) cohort for interventions is P4 (community), which is a collective agency of 10 000 persons. This cohort scale optimizes the highest reduction (179 Gt) of CO$_2$e concentrations and offers the highest number (56) of implementable climate actions. The climate actions implementable at the sweet spot span every sector and includes all climate actions from the land use sector (details in table 2). However, the highest financial benefit (~10 trillion USD) from climate actions is obtained at P5 (metacommunity of 100 000 persons), compared to ~ 8 trillion USD at the systemwide sweet spot (P4). Consequently, the community scale is where the majority of CO$_2$e reduction can be most effectively incubated and scaled.

1. The authors independently established an initial set of suitable P10 cohort or cohort ranges for deploying and implementing each of the climate solutions through individual, proxy and/or collective agencies based on reviewing related literature (mostly cited in the references for PD), real world examples and their own professional expertise.

2. The PD team members recommended P10 cohort ranges that were in line with the assumptions of agency on their analysis. Each of the authors independently suggested an alternative set of P10 cohort ranges if they disagreed with the PD suggested cohorts.

3. The individual author cohort suggestions were combined with the PD recommendations to arrive at the final set (intersection set) of P10 cohorts with the highest authors-PD agreement, which were regarded as a robust and the most suitable set of cohorts for the implementation of each climate solution.

4. The final set of P10 cohorts was further revised and evaluated through discussions among authors as well as with external experts.

Methods for calculating of cumulative greenhouse gas emission reduction and achieved financial benefit in each cohort, geographic scale and transformation sphere, and the sweet spot for impact maximization are provided in the supplementary materials.

3. Results and discussion

3.1. Sweet spots for optimizing agency and impacts

Assessing 72 market-ready, scalable climate adaptation and mitigation solutions from PD, we found that the systemwide optimum population cohort for the climate action interventions is a community (P4) of 10 000 persons (figure 2). This scale optimizes the highest reduction (cumulative 179 Gt during 2020–2050 against the RES) of CO$_2$e concentrations and the highest number (56) of implementable climate solutions (figure 2). Moreover, we find that almost half of the CO$_2$e reduction (46%, cumulative 480 Gt CO$_2$e during 2020–2050 against the RES) can be obtained across the P4 (community of 10 000 persons) to P6 (urban area/region of 1 000 000 persons) cohorts, along with 64% of the total economic benefit achieved (figure 2). P4 to P6 also represent the top three cohorts for the net CO$_2$e reduction and climate action benefits. Hence, prioritizing climate actions at community to urban (P4 to P6) scale may likely complement and amplify global top-down and local bottom-up efforts to support rapid sustainability transformations. Indeed, individual agency and leadership coupled with effective policies and incentives at state, national and international scales are imperative, but our findings indicate that for most climate actions, focus for leverage and transformations may be most effectively placed at the community to urban scale. They also support recent work on low energy-demand scenarios for meeting the Paris target

Table 2. Project Drawdown (PD) climate solutions that have been included in our analysis. The **bold** climate solutions are implementable at the sweet spot (P4). The climate solutions are grouped into sectors previously determined by PD. We assigned ranges of Powers of 10 (P10) cohorts for each climate solutions and calculated median of the assigned cohorts for each climate solution and sectors. The net carbon dioxide equivalent concentration (CO_2e) reduction and benefit from those climate solutions and sectors are extracted and calculated using the 'Plausible Scenario'. Negative benefits indicate losses when compared to the cumulative implementation and operational cost in the reference emission scenario during the 2020–2050 period. However, this may be different when calculated for the lifetime of a climate solution, e.g. insulation, which becomes a net financial benefit as a result of lifetime operational savings after 2050 but has a high prior cost. N/A values for net benefit indicate that high geographic and sectoral variability inhibited the calculation or they were calculated in other climate solutions. For technical details on the drawdown models, data, assumptions and procedures, readers are referred to Hawken (2017) and the Project Drawdown website: www.drawdown.org.

Overall Rank	Climate Solutions	Sectors	Suitable P10 Cohort Ranges	Median of the P10 Cohort Range	Projected CO_2e reduction by 2050 (in Gt (%))	Net economic benefit, 2020–2050 (billion USD)
25	**LED Lighting**		**1–6**	**3.5**	**12.85**	**2700.7**
28	**District Heating**		**4–6**	**5**	**9.38**	**3086.43**
31	**Insulation**		**1–5**	**3**	**8.27**	**−1142.59**
41	**Heat Pumps**		**1–5**	**3**	**5.2**	**1427.95**
43	**Building Automation**		**2–5**	**3.5**	**4.62**	**812.43**
51	**Walkable Cities**		**3–6**	**4.5**	**2.92**	**NA**
54	Smart Thermostats	*Buildings*	1–2	1.5	2.62	714.26
55	**Land fill Methane**	*and*	**4–6**	**5**	**2.5**	**69.39**
56	**Bike Infrastructure**	*Cities*	**4–6**	**5**	**2.31**	**2427.44**
58	**Smart Glass**		**2–4**	**3**	**2.19**	**−607.2**
67	**Water Distribution**		**3–7**	**5**	**0.87**	**765.74**
69	**Green Roofs**		**1–5**	**3**	**0.77**	**−404.83**
	Aggregate Buildings and Cities		*1–7*	*4*	*54.5 (5.19%)*	*9849.72 (25.63%)*
1	Wind Turbines (Land and Ocean)		5–7	6	98.7	5901.8
8	**Solar Farms**		**4–7**	**5.5**	**36.9**	**5104.44**
10	**Rooftop Solar**		**1–5**	**3**	**24.6**	**3004.49**
18	Geothermal		5–7	6	16.6	1179.82
20	Nuclear		6–8	7	16.09	1712.52
24	Concentrated Solar		5–7	6	10.9	−905.85
27	**Methane Digesters (Small and Large)**	*Energy*	**1–7**	**4**	**10.3**	**−53.78**
30	Wave and Tidal		5–7	6	9.2	−1416.54
33	**Biomass**		**3–7**	**5**	**7.5**	**117.04**
39	**Solar Water**		**1–4**	**2.5**	**6.08**	**770.66**
46	**In-Stream Hydro**		**3–5**	**4**	**4**	**365.83**
48	**Cogeneration**		**2–4**	**3**	**3.97**	**287.68**
64	Waste-to-Energy		5–7	6	1.1	−16.18
72	**Micro Wind**		**1–4**	**2.5**	**0.2**	**−16.22**
	Aggregate Energy		*1–8*	*5*	*246.14 (23.44%)*	*16 035.71 (41.73%)*
3	**Reduced Food Waste**		**0–4**	**2**	**70.53**	**NA**
4	Plant-Rich Diet		0–1	0.5	66.11	NA
9	**Silvopasture**		**1–8**	**4.5**	**31.19**	**657.78**
11	**Regenerative Agriculture**		**1–8**	**4.5**	**23.15**	**1870.88**
14	**Tropical Staple Trees**		**1–8**	**4.5**	**20.19**	**506.9**
16	**Conservation Agriculture**		**1–8**	**4.5**	**17.35**	**2081.54**
17	**Tree Intercropping**		**1–8**	**4.5**	**17.2**	**−124.89**
19	**Managed Grazing**		**1–8**	**4.5**	**16.34**	**684.79**
21	Clean Cookstoves	*Food*	1–2	1.5	15.81	94.12
22	**Improved Rice Cultivation and System of Rice Intensification**		**1–8**	**4.5**	**14.47**	**NA**
23	Farmland Restoration		1–8	4.5	14.08	1270.23

Table 2. Continued.

Overall Rank	Climate Solutions	Sectors	Suitable P10 Cohort Ranges	Median of the P10 Cohort Range	Projected CO$_2$e reduction by 2050 (in Gt (%))	Net economic benefit, 2020–2050 (billion USD)
29	**Multistrata Agro-forestry**		**1–8**	**4.5**	**9.28**	**682.99**
57	**Composting**		**3–6**	**4.5**	**2.28**	**2.9**
61	**Nutrient Management**		**1–8**	**4.5**	**1.81**	**NA**
63	**Farmland Irrigation**		**1–8**	**4.5**	**1.33**	**213.51**
68	**Biochar**		**2–4**	**3**	**0.81**	**NA**
	Aggregate Food		*0–8*	*4*	*321.93 (30.66%)*	*7940.75 (20.67%)*
5	**Tropical Forests**		**3–8**	**5.5**	**61.23**	**NA**
12	**Temperate Forests**		**3–8**	**5.5**	**22.61**	**NA**
13	**Peatlands**		**3–8**	**5.5**	**21.57**	**NA**
15	**Afforestation**		**2–4**	**3**	**18.06**	**968.41**
34	**Bamboo**		**2–4**	**3**	**7.22**	**216.29**
37	**Forest Protection**		**3–8**	**5.5**	**6.2**	**NA**
40	**Indigenous Peoples' Land Management**	*Land Use*	**3–8**	**5.5**	**5.25**	**NA**
49	**Perennial Biomass**		**1–4**	**2.5**	**3.33**	**NA**
50	**Coastal Wetlands**		**3–8**	**5.5**	**3.19**	**NA**
	Aggregate Land Use		*1–8*	*5*	*148.66 (14.16%)*	*1184.7 (3.08%)*
2	**Refrigerant Management**		**2–6**	**4**	**89.74**	**NA**
35	**Alternative Cement**		**4–5**	**4.5**	**6.69**	**NA**
44	Water Saving—Home		1–2	1.5	4.61	1727.68
45	**Bioplastic**		**2–4**	**3**	**4.3**	**NA**
52	**Household Recycling**	*Materials*	**3–6**	**4.5**	**2.77**	**−295.79**
53	**Industrial Recycling**		**3–6**	**4.5**	**2.77**	**−295.79**
66	**Recycled Paper**		**1–4**	**2.5**	**0.9**	**NA**
	Aggregate Materials		*1–6*	*4*	*111.78 (10.65%)*	*1136.1 (2.96%)*
26	Electric Vehicles		0–1	0.5	10.8	−4421.63
32	**Ships**		**3–4**	**3.5**	**7.87**	**−491.55**
36	**Mass Transit**		**4–6**	**5**	**6.57**	**NA**
38	**Trucks**		**2–5**	**3.5**	**6.18**	**2238.09**
42	**Airplanes (Improvements)**		**3–5**	**4**	**5.05**	**2525.38**
47	Cars (Hybrids, etc)	*Transport*	0–1	0.5	4	2360.41
60	**Telepresence**		**1–4**	**2.5**	**1.99**	**1182.87**
62	**High-Speed Rail**		**5–8**	**6.5**	**1.52**	**−739.19**
65	Electric Bikes		0–1	0.5	0.96	119.32
70	**Trains**		**3–5**	**4**	**0.52**	**−494.78**
71	Ridesharing		0-1	0.5	0.32	NA
	Aggregate Transport		*0–8*	*3*	*45.78 (4.36%)*	*2278.92 (5.93%)*
6	**Family Planning**		**0–4**	**2**	**59.6**	**NA**
7	**Educating Girls**	*Women and Girls*	**0–4**	**2**	**59.6**	**NA**
59	Women Smallholders		1–2	1.5	2.06	NA
	Aggregate Women and Girls		*0–4*	*2*	*121.26 (11.55%)*	*NA (NA)*
	Overall Aggregate		*0–8*	*4*	*1051.01 (100%)*	*38 425.9 (100%)*

that emphasize technological granularity, a sharing economy and decentralized energy systems for rapid transformations (Grubler *et al* 2018), and successful community and urban scale climate actions in the global South (Nagendra 2018, Bai *et al* 2018).

Practically, for engaging stakeholders (ideally including representation across the community) and decision makers and change agents, especially those who shape policy and control funding, the sweet spot range between P4 (community of 10 000 persons) and P6 (urban area/region of 1 000 000 persons) is not too big, not too small, but just right. It allows for actions to be localized and customized for the culture, location and circumstances rather than relying on individual efforts or top-down mandates to accrue up or trickle down. Take, for example, the global implementation of 'Silvopasture' system, also referred to as 'agroforestry', which combines grazing of livestock in woodlands and has the potential of 31.19 Gt CO_2e reduction and 657.78 billion USD economic benefit by 2050 (Hawken 2017). To achieve this will require an expansion of global Silvopasture coverage (through projects of planting trees in open pasture and thinning plantation canopies to allow for forage growth) from 351 million acres to 554 million acres by 2050, involving people spanning from household (P1) up to the sub-continental scale (P8) (details in table 2). A global implementation of those actions is not suitable at either extreme of this range due to financial, technical or practical challenges, but the P10 framework calculates that the suitable scale for agency and impact between the household and sub-continental scales would be between P4 and P5, an agency between 10 000 and 100 000 persons (table 2). The sweet spot range is not suggested as the exact number of people to directly engage, but rather the number impacted through implementing Silvopasture at scale by farmers, agriculture extension agents, and related business and policy leaders advocating for this innovation intervention.

The implementation of a climate solution requires policy and infrastructure support from multiple (and sometimes all) P10 cohorts, although the first-hand implementation will take place in a limited range of cohorts, where people have the most to gain or lose. Hence, some of our estimates of the sweet spots may seem nuanced, where other experts may disagree with our estimation. For example, in the case of Electric Vehicles (EV), the suitable level of agency was estimated to be at the individual (P0) to family (P1) cohorts. We were aware of the considerable effort industry and governments have put into encouraging EV adoption through market driven technological improvement, e.g. cheaper technology, better and more efficient EVs, and smart policy design, e.g. banning the sales of fossil fuel cars, but our experts agreed that agency focused primarily at this scale hasn't been effective. As observed by Bernstein and Hoffmann (2019), expensive state-level actions to encourage

deployment of EV through incentives has displayed a 'double trap' dynamic, with consumers using their EV as second cars and to denote status rather than primary vehicles, continuing to rely on fossil fuel for their mobility. Other nations working with industry have struggled as well to encourage EV adoption and run into a lack of consumer demand, meaning that at this juncture individuals and families are the 'deciders' with agency over whether or not EV will become an integral part of the mobility solution. Hence, we suggest that efforts to encourage adoption of EV needs to be done at a more granular level. However, participation of all actors at international, national, industry and household consumer levels are indeed crucial for successful deployment of EVs.

Our findings (re)emphasize the importance of the role of cities and cities networks in climate actions. As nations fail to follow-through on their commitments, for a range of political and economic reasons, cities, through the work of organizations such as C40 and ICLEI, have attempted to help address the gap (Watts 2017), with some degree of success (Davidson *et al* 2019). The efforts of these subnational and non-state actors to share effective practices and build capacity through collective impact and agency demonstrate the effectiveness of focusing on the sweet spot range.

The sweet spots for PD's eight sectors (electricity generation, food, women and girls, transport, buildings and cities, land use, materials and coming attractions) ranged from a low of P2 (personal network of 100 persons) for women and girls to a high of P5 (metacommunity of 100 000 persons) for energy and land use sectors (details in table 2). The sweet spots for the largest and the smallest sectors (food and transport, 30.66% and 4.36% of the total cumulatively reduced CO_2e during 2020–2050 against the RES, respectively) are P4 (community of 10 000 persons) and P3 (village of 1000 persons), respectively. Consequently, even as larger-scale policies and financial support are often required for maximizing economies and sublinear efficiencies of scale, our findings suggest that a distributed and localized approach is likely the key for scaling climate actions at the extent needed for halving anthropogenic CO_2e emissions every decade in order to meet the Paris Agreement target (Rockström *et al* 2017, Intergovernmental Panel on Climate Change 2018). Decision-makers and change agents in every sector and location can apply this approach to determine their own ideal practical range for deploying the greatest number of appropriate and implementable climate actions to reach the greatest benefits.

3.2. Geographic scales and transformation spheres

Recognizing the semantic challenges and imprecision inherent in mapping the spatial with human population scales and their varied concentrations, we propose that the term 'local', by median population, may generally be applied from P0 (individual) to

P6 (urban/region), and 'regional' can span from P7 (nation/sate) to P9 (continental) (details in figure 3(a)). Based on this spatialization of population cohorts, we find a cumulative reduction of 853.23 Gt and 196.82 Gt CO_2e during 2020–2050 against the RES from the local and regional scales, respectively, while all 72 PD solutions are implementable and/or influenced initiating at the local scale (figure 3(a)). Thus, the P10 framework helps to examine how population scales are spatially nested together, allowing us to methodically 'zoom' in and out from the individual to global scales. Further research will explore in more details the connections between P10 and other cross-scale frameworks that examine the spatial structures and systems of society and the planet (Landauer *et al* 2018).

In the three overlapping and interacting 'transformation spheres' proposed by O'Brien and Sygna (2013), we find the P0 (individual) to P2 (personal network) cohorts appear to most closely correspond to the personal sphere, where changes in norms, beliefs and mind-set take place, e.g. plant-rich diet (details in figure 3(b)). A broad range of P10 cohorts, i.e. P3 (village) to P9 (continental), correspond to the political sphere, often with multiple layers of decision-making and governance impacting individuals and communities. The ultimate cumulative effects of transformations in the personal and political spheres culminate in the practical sphere (behavioral and technical responses), which in the case of global climate change correspond to the global (P10) cohort. Applying our analysis of PD data, we find that a cumulative net reduction of 241.82 Gt and 808.23 Gt CO_2e during 2020–2050 against the RES can be achieved through the transformations of personal and political spheres, respectively (figure 3(b)). Thus, a higher net CO_2e reduction and benefit can be achieved in the political sphere than in the personal sphere, when multiple intersecting layers of government, human-social and economic interests and activities are represented and amplified (Alesina 2003).

Note that geographic regions and social spheres may also be shaped by the scope, type and context of climate and sustainability actions required, which may also shape the suitable scale for agency based on the available capacities to take those actions in those geographic regions and social spheres. For example, generation and distribution of geothermal energy may predominantly require actions from the individuals, social networks and institutions based in and affected by the geopolitics of the regions around the tectonic plates whereas shifting to plant-rich diet requires an agency of behavioral change of individuals, families and communities globally (Hawken 2017). The P10 framework may help cascading and disseminating the impact from various actions, practices and solutions from diverse geographic regions and social spheres as well as

may assist in identification of solutions suitable for deployment within different regions and spheres.

3.3. Where local and global converge
While every intervention is unique and dependent upon a wide array of contexts and factors, whether for climate actions or other efforts to reduce risks and increase resilience, based on our findings, it appears that our original hypothesis of a sweet spot for collective agency and impact around the P5 scale, where the local and global converge, was correct. Policies and actions occur at all scales, and the P10 framework supports decision-makers—from individuals and households to local planners and mayors, to regional and nation state governance officials, to business owners and international leaders. We propose that the optimization process that we have applied using the P10 framework may offer a tool for examining the range and scaling of climate actions and related sustainability goals and practices, including public health. It may assist in targeting suitable climate actions at scale, tailoring relevant narratives, and calibrating policies to address the urgency of implementing interventions to rapidly reduce greenhouse gas concentrations.

We acknowledge that our approach assumes a positive view toward individual, collective and overall social agencies that does not necessarily factor in the efforts to prevent change of the fossil fuel status quo (Otto *et al* 2020). Vested interests, institutional inertia, fossil fuel subsidies and investments, and concerns of social unrest or collapse all are factors that maintain the status quo and limit or counter agency toward climate actions. Thus, our approach assumes the Paris Agreement and related efforts are actual, achievable aspirations of the nations of the world.

Note that we explicitly focus on one critical aspect of social complexity, i.e. the number of people (P10 cohorts and cohort ranges) to form agency of climate and sustainability actions. However, the content, direction, forms and impact of climate and sustainability actions are dependent on many intertwined factors and dynamics of social and structural complexity, and the nature and dynamics of the individuals, such as degrees of freedom, distinct capacities, personalities, modalities of actions, learning curves, decisions and options related to consumption and production patterns (Tàbara *et al* 2010). Particularly, as we indicated, while a larger P10 cohort entails a larger impact by implementing a solution, it also incorporates a higher level of embedded social and structural complexity. Moreover, the willingness, incentives, options, access, possibilities and resources of individuals and institutions for climate and sustainability actions contextually vary across the P10 cohorts and cohort ranges because of large economic, educational and political inequalities. Hence, although these ranges of factors of social and structural complexity were not included in our analysis
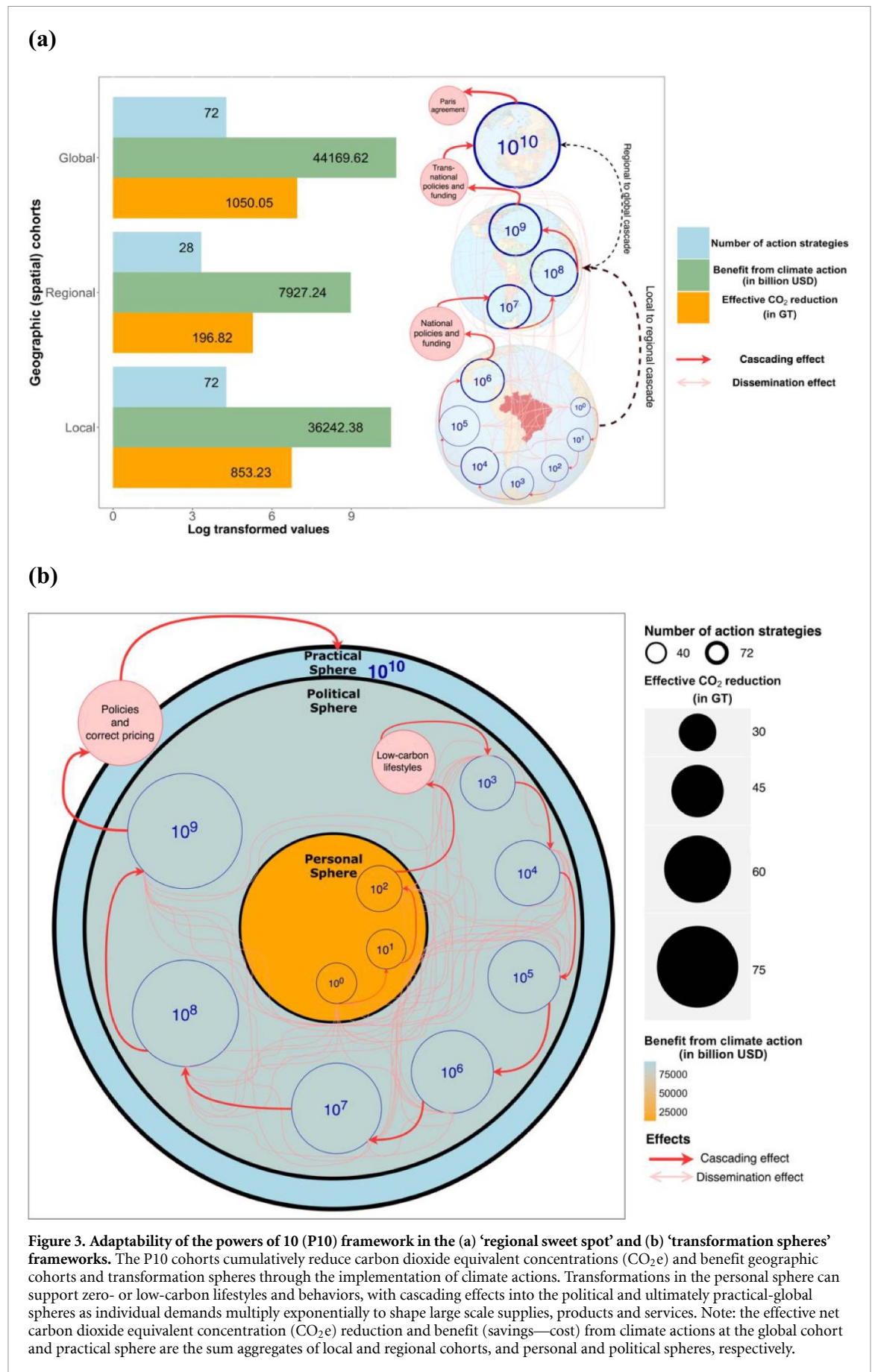
Figure 3. Adaptability of the powers of 10 (P10) framework in the (a) 'regional sweet spot' and (b) 'transformation spheres' frameworks. The P10 cohorts cumulatively reduce carbon dioxide equivalent concentrations (CO_2e) and benefit geographic cohorts and transformation spheres through the implementation of climate actions. Transformations in the personal sphere can support zero- or low-carbon lifestyles and behaviors, with cascading effects into the political and ultimately practical-global spheres as individual demands multiply exponentially to shape large scale supplies, products and services. Note: the effective net carbon dioxide equivalent concentration (CO_2e) reduction and benefit (savings—cost) from climate actions at the global cohort and practical sphere are the sum aggregates of local and regional cohorts, and personal and political spheres, respectively.

and many were clearly beyond the scope, we offer the P10 framework as a lens to understand the social and structural complexity by zooming in on

each of the cohorts and analyzing context, including geophysical and climatic characteristics, socio-economic, political and cultural dynamics, existing and potential energy, food and water resources, and overall vulnerabilities, obstacles and opportunities for resilience-building. Existing frameworks, such as the SEIC Model (Tàbara and Pahl-Wostl 2007), which involves examining the structure of norms and institutions (S), the use and availability of energy and resources (E), the kinds of information and knowledge systems (I) and the cumulative environmental change which also influences the dynamics of all the former components (C), will help inform and guide this analysis of the complexities and entanglements around each cohort and the sweet spot of metacommunity scale. Thus, P10 will provide a more granular yet composite understanding of populations at a subnational scale, allowing for more equalized comparisons by population and location rather than the inherently unequal comparisons by nation states. This metacommunity analysis will help in better identifying the socio-geographical characteristics and ideally the social networks and institutions involved in supporting or obstructing actions to address global challenges on a more localized scale.

This P10 framework is already being applied in the domain of climate change education (Kwauk 2020) to examine the landscape of climate learning, from the international and national scales to the school, classroom and learner and in the advancement of quantum social theory as it applies to climate change (O'Brien 2016). Future studies should examine the implications of quantum social theory, including fractal self-similarities between scales, entanglement, global non-linear and non-local dynamics, complementarity and uncertainty, which add depth and complexity, potentially enhancing our ability to examine and harness the interdependencies and interconnections between agency at scale and through time. An important next step will be to develop short term (e.g. two year) and decadal strategies that identify barriers and opportunities to create and increase climate actions agency in persons and systems through 'public awareness, education and engagement' as called for in article 12 of the Paris Agreement (UNFCCC 2017b, Rodriguez and Morrison 2019). Our findings suggest that efforts to optimize climate literacy, empowerment, capital deployment, and actions in order to rapidly scale climate actions should take into consideration how scales overlap and interact but generally focus at the sweet spot between the range of P4 (10 000 persons) and P6 (1 000 000 persons) (Hsu *et al* 2019).

In the decades since the signing of the UNFCCC, climate actions has been primarily left in the hands of technical experts, scientists and politicians, with little opportunity for the public or individuals to take an active role in the transformations away from fossil

fuels and toward the regenerative practices required (Wilson 2012, Hale 2016, Hsu *et al* 2017). The P10 framework and our analysis may suggest a means for people—students, youth activists, stakeholders in every sector and working at every scale of society—to consider the systems they are embedded in and allow them opportunities to become more fully involved with climate actions, as was envisioned in the original UNFCCC, where Parties agreed they would foster public awareness and participation 'in developing adequate responses to climate change and its impacts' (UNFCCC 2017a). Moreover, as an analytic tool, the P10 framework may help frame quantum concepts (O'Brien 2016), including 'entanglement, complementarity, uncertainty, and superposition', which may provide a strong basis for recognizing and promoting people as the solution to climate change, and allowing us to recognize that we are 'not agents but agency itself.' To conclude, our findings answer Goffman's question (Goffman 2020) 'is glocalization our sustainability future?' in the affirmative, and we agree with his conclusion that a new version, with people who are aware of global trends and challenges are rooted deeply in their communities, is imperative.

Data and materials availability

The Plausible scenario data from Project Drawdown used in this study are available from Hawken (2017)[16] and Project Drawdown website: http://drawdown.org. Data for other scenarios can be obtained by request to Project Drawdown team.

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