Powers of 10: cross-scale optimization of social agencies for rapid climate and sustainability action

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Abstract

Achieving the goals of the Paris Agreement and related sustainability initiatives will require halving of 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 transformation and novel governance solutions. A new "Powers of 10" (P10) logarithmic optimization framework offers a social perspective and practical tool for climate action by complementing technology, business, finance and policy paradigms and existing governance frameworks. P10 identifies optimal population cohorts for climate action 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, we find prioritizing community to urban-focused climate action can help maximize top-down and bottom-up efforts, and support policies and practices for rapid sustainability transformation.

While there is almost unanimous international agreement to the aspirational goals of rapid reduction of greenhouse gases set forth in the Paris Agreement [1] and related initiatives such as the Sustainable Development Goals (SDGs) [2], 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 [3]. However, plans for deploying multi-scale climate action frequently rely on relative and subjective terms such as "national", "state", "regional", "community", and "local" to frame the populations involved [3]. Usage of such terminology lacks the precision necessary for strategic innovation and decision-making to deploy actions leading to greenhouse gas reduction, adaptive technologies and strategies, and heightened quality of family and community life [3,4]. Additionally, some scales may be more important for effective implementation of climate action than others [4].

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 experts, i.e. Nationally Determined Contributions (NDCs) [4,5]. 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 [6] (details in Supplementary Table S1). Focusing on nation states 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 sectors of society [1,7]. However, well before the Paris Agreement, there have been scores of efforts to mobilize climate action and support sustainable practices in subnational and nongovernmental entities [8,9]. 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 action 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 [10]. 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 action are often misleading [3,4]. While existing hierarchical societal frameworks are important tools for understanding structural dynamics [3,8,9], there has been no accessible framework to methodically examine the optimal number of people needed for successful implementation of climate action.

Here we propose the logarithmic "Powers of 10 (P10)" framework to overcome the relative and subjective bias in the existing approach to climate action and help identify individual, proxy and collective "social agencies" (details in Supplementary Materials and Methods), and corresponding systemic and institutional dynamics and policies across scales (Fig. 1). By using the ten orders of magnitude between a single individual and the projected ~10 billion global population by 2050, we place people in the climate mitigation and adaptation equation. 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 [8]. Driving our research was the question of how to discern optimal interventions for the strategic deployment of climate action and the related economic and social policy instruments and technologies that will achieve economic benefits and carbon dioxide equivalent (CO_{2e}) reductions [11].

As demonstrated by "Carbon Law" and addressed in detail in the Intergovernmental Panel on Climate Change (IPCC) 1.5^{0}C emission pathways [12,13], CO_{2e} 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 [7]. The unprecedented climate action required for halving emissions mandates rapid scaling up of adaptation and mitigation measures in all sectors through leadership and social transformation that optimize social agencies with maximized impact at appropriate scale [14,15]. The number of persons in each P10 cohort represents a critical mass for forming social agency, which is the capacity to make decisions, influence actors and take actions at the appropriate scale, and implement and benefit from the action first hand. Thus, the P10 framework adds value and precision to existing cross-scale frameworks, thereby helping target social agency and interventions for climate action by emphasizing transformation at scale [8].

Drawing upon a robust dataset from Project Drawdown (PD) "Plausible scenario" [16], we modeled the potential contribution of each of the cohorts of our P10 framework to the net reduction of CO_{2e} concentrations and the net economic benefit achieved between 2020-2050. We also examine whether and how P10 relates to geographic scaling [4,11], and, as an example of overlap with other cross-scale frameworks, demonstrate P10's synergy with the "transformation spheres" theory [17], where social transformation is depicted as a process taking place across embedded and interacting personal, political, and practical realms.

Sweet spots for optimizing agency and impacts

The iterative process we employed to determine the ideal P10 cohort range for each action is described in detail in Supplementary Materials and Methods, but the basic formula is straight forward. 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 [16]. 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 optimal at either extreme of this range due to financial, technical or practical challenges, but the P10 framework calculates that the optimal 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). This suggests that for globally implementing the Silvopasture system there is a sweet spot where the ability to act is optimized and the collective climate impact and benefits derived from economies of scale for people (including future generations) is maximized.

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 (Fig. 2). This scale optimizes the highest reduction (179 gigatons (Gt)) of CO_{2e} concentrations and the highest number (56) of implementable climate actions (Fig. 2). Moreover, we find that almost half of the CO_{2e} reduction (46%, 480 Gt CO_{2e}) 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 (Fig. 2). P4 to

P6 also represent the top three cohorts for the net CO_{2e} reduction and climate action benefits. Hence, prioritizing climate action 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 transformation. These findings also support recent work on low energy-demand scenarios for meeting the Paris target that emphasize technological granularity, a sharing economy and decentralized energy systems for rapid transformation [18], and successful community and urban scale climate action in the global South [9,19] .

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 reduced CO_{2e}, respectively) are P4 (community of 10,000 persons) and P3 (village of 1,000 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 action at the rate needed for halving anthropogenic CO_{2e} emissions every decade in order to meet the Paris Agreement target [12,13]. Decision-makers in every sector and location can apply the P10 framework to determine their own ideal practical range for deploying the greatest number of appropriate and implementable climate action to reach the greatest benefits.

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 Fig.3a). Based on this spatialization of population cohorts, we find a cumulative reduction of 853.23 Gt and 196.82 Gt CO_{2e} from the local and regional scales, respectively, while all 72 PD solutions are implementable and/or influenced initiating at the local scale (Fig.3a). 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 [8].

In the three "transformation spheres" [17], we find the P0 (individual) to P2 (personal network) cohorts correspond to the personal sphere, where changes in norms, beliefs and mind-set take place, e.g. plant-rich diet (details in Fig.3b). 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 cumulative effects of transformation in the personal and political sphere are measured at the practical sphere (behavioral and technical responses) corresponding to the global (P10) cohort. We find that a net reduction of 241.82 Gt and 808.23 Gt CO_{2e} can be achieved through the transformation of personal and political spheres, respectively (Fig.3b). Thus, a higher net CO_{2e} reduction and benefit can be achieved in the political sphere, when multiple intersecting layers of government, human-social and economic interests and activities are represented and amplified [6].

Where local and global converge

Policies and action 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 P10 framework's optimization process offers an accessible tool for examining the range and scaling of climate action and related sustainability goals and practices. It may assist in targeting optimal climate action, tailoring relevant narratives, and calibrating policies to address the urgency of implementing interventions to rapidly reduce greenhouse gas concentrations.

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 action agency in persons and systems through "public awareness, education and engagement" as called for in article 12 of the Paris Agreement [1,20]. Our findings suggest that efforts to optimize climate literacy, empowerment, capital deployment, and action in order to rapidly scale climate action 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).

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 [15]. 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 action [21]. Thus, our approach assumes the Paris Agreement and related efforts are actual aspirations of the nations of the world.

To conclude, the new P10 framework has the potential value of being flexible and adaptable enough to serve as a tool for cross-scale analysis, providing perspective on the structures and systems, obstacles and opportunities that are required for optimizing agencies for climate action and sustainable practices. While all scales are important to achieve success, we show that prioritizing community to urban-focused climate action is the single most important evidence-based paradigm shift we can take to support rapid greenhouse gas reductions, carbon sequestration and progress towards attainment of the Paris Agreement and SDGs.

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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.

Figure legends

Fig. 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. 10^0 - 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).

Fig. 2. Numbers of implementable climate action, effective net CO_{2e} reduction and benefit (savings - cost) from climate action 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_{2e} concentrations and offers the highest number (56) of implementable climate action. The climate action implementable at the sweet spot span every sector and includes all climate action 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_{2e} reduction can be most effectively incubated and scaled.

Fig. 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 action strategies. Transformation 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 action at the global cohort and practical sphere are the sum aggregates of local and regional cohorts, and personal and political spheres, respectively.

Tables

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)
10^0	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

Table 2. Project Drawdown (PD) climate solutions that have been included in our analysis. The grey highlighted 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 fossil fuel-based system or when climate solutions were not implemented 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) *(12)* and the Project Drawdown website: www.drawdown.org.

Overall Rank	Climate Solutions	Sectors	P10 Cohort Range	Median of the P10 Cohort Range	Projected CO_{2e} reduction by 2050 (in Gt (%))	Net economic benefit, 2020-2050 (billion USD)
25	LED Lighting	*Buildings and Cities*	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		1-2	1.5	2.62	714.26
55	Land fill Methane		4-6	5	2.5	69.39

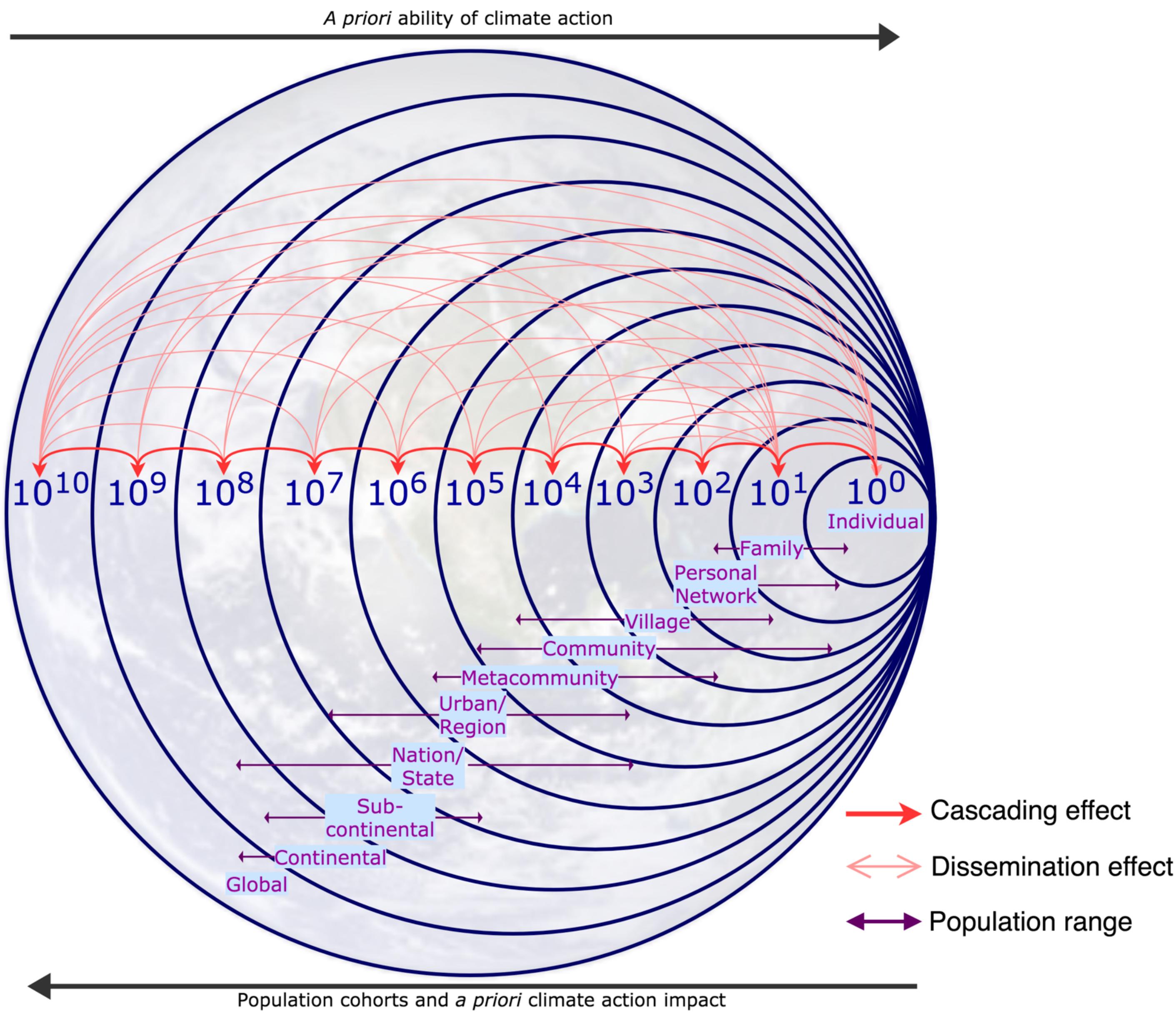
56	Bike Infrastructure		4-6	5	2.31	2427.44
58	Smart Glass		2-4	3	2.19	-607.2
67	Water Distribution		3-7	5	0.87	765.74
69	Green Roofs		1-5	3	0.77	-404.83
	Aggregate Buildings and Cities		*1-7*	*4*	*54.5 (5.19%)*	*9849.72 (25.63%)*
1	Wind Turbines (Land and Ocean)	*Energy*	5-7	6	98.7	5901.8
8	Solar Farms		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)		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%)*	*16035.71 (41.73%)*
3	Reduced Food Waste	*Food*	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		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
29	Multistrata Agroforestry		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	*Land Use*	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		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	*Materials*	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		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	*Transport*	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.)		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	*Women and Girls*	0-4	2	59.6	NA
7	Educating 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%)***	***38425.9 (100%)***

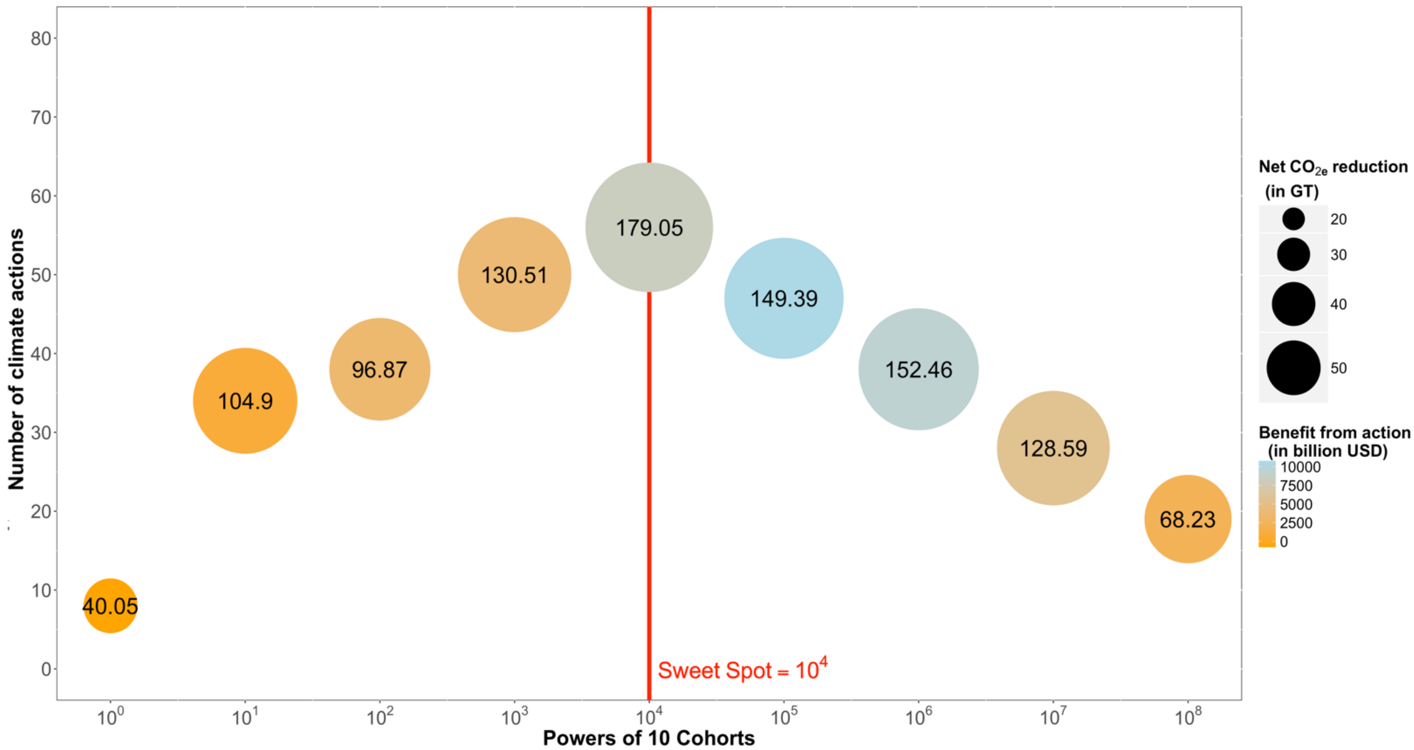
Figures

Fig. 1.



340 **Fig. 2.**

341

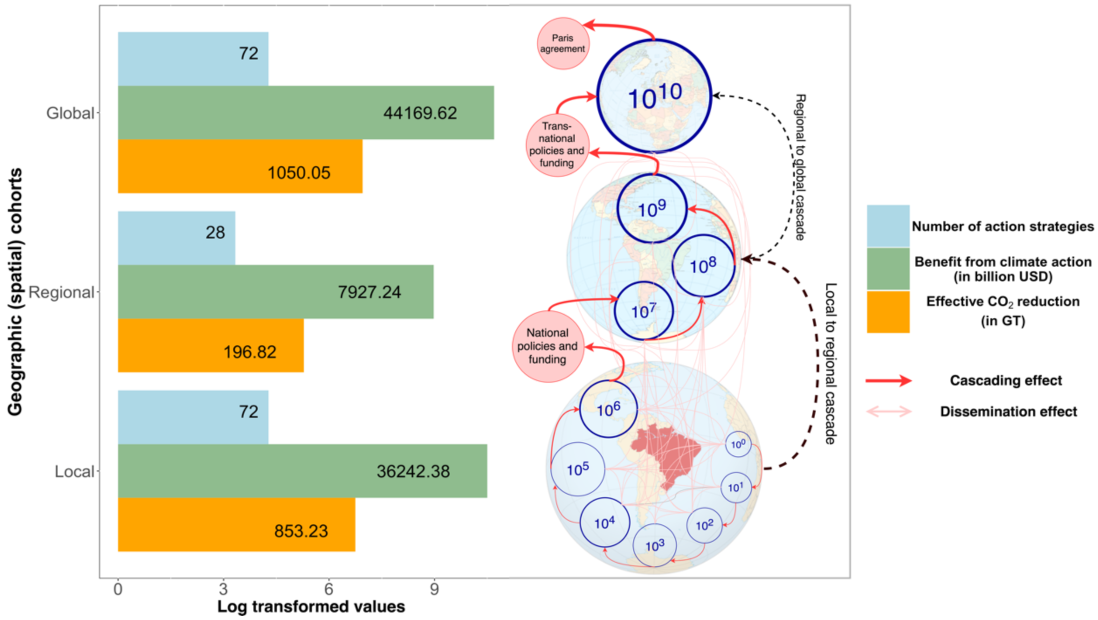


342

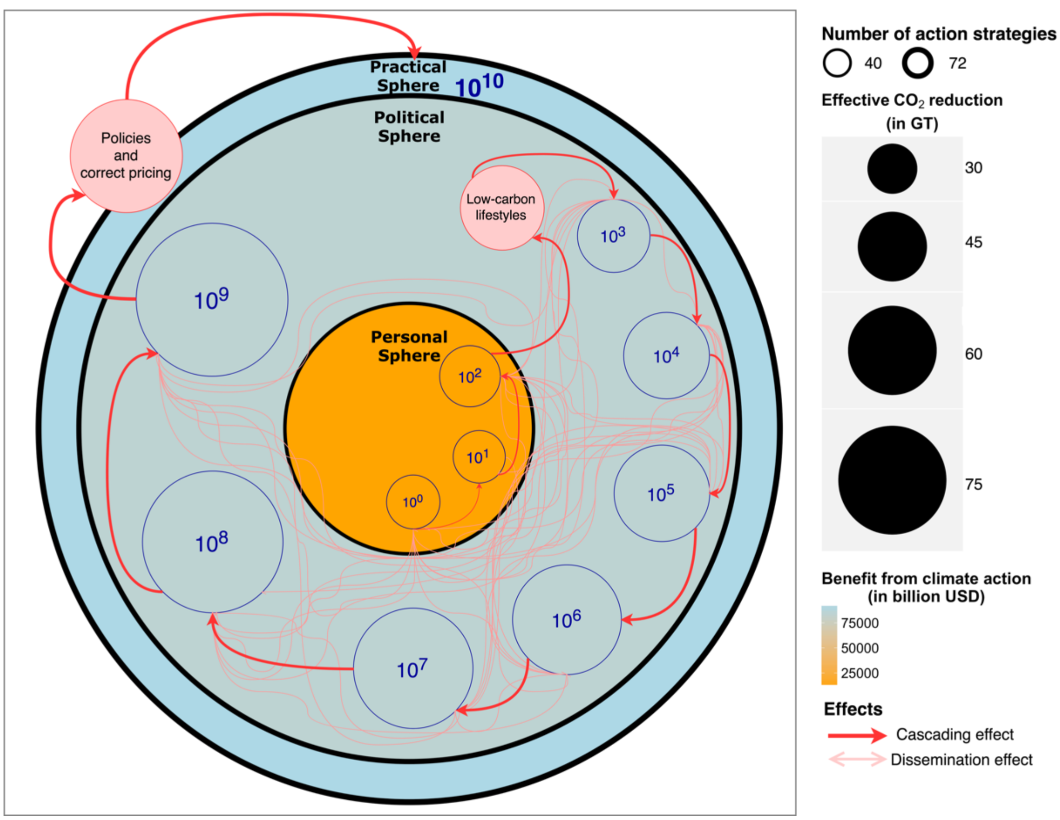
343

Fig. 3.

(a)


Geographic (spatial) cohorts
Global
Regional
Local
72
44169.62
1050.05
28
7927.24
196.82
72
36242.38
853.23
0
3
6
9
Log transformed values
Paris agreement
Trans-national policies and funding
National policies and funding
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Regional to global cascade
Local to regional cascade
Number of action strategies
Benefit from climate action (in billion USD)
Effective CO_2 reduction (in GT)
Cascading effect
Dissemination effect

(b)


Practical Sphere
Political Sphere
Personal Sphere
Policies and correct pricing
Low-carbon lifestyles
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Number of action strategies
40
72
Effective CO_2 reduction (in GT)
30
45
60
75
Benefit from climate action (in billion USD)
75000
50000
25000
Effects
Cascading effect
Dissemination effect