nature climate change

Analysis

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Expert review of the science underlying nature-based climate solutions

In the format provided by the authors and unedited

Supplementary Information

Contents

SUPPLEMENTARY INFORMATION: APPENDIX A

Table 1**.** Forty-three NbCS pathways listed by mean confidence in the sufficiency of the scientific basis to support development of high-quality carbon credits, their current carbon crediting protocols and activity, and the estimates of potential GHG impact (Pg CO_2e yr^{-1}), with percentiles scaled to the $20^{th}/80^{th}$ credible interval using methods from Hemming et al. 2018 (if the interval became negative in the scaling, it was set to zero, as the purpose here was not evaluating the science of potential sources). For pathways ranked as Category 3, meaning there is insufficient scientific basis for making credible estimates of GHG impact potential, estimates of impact potential were not requested (see methods), and if given were dropped for consistency with survey design (see SI 1 Appendix A for survey instrument). Numbers here are from the expert elicitation, synthesizing the literature. For more information on specific pathways and estimates from other studies, see SI 2.

Pathway	**Mean category rank**	**SD**	**20th cat. percent.**	**80th cat. percent.**	**Percent. range**	**Credit protocols**	**† Market Activity**	**Median impact potential (Pg CO2e/yr)**	**20th percentile CI (impact potential)**	**80th percentile CI (impact potential)**	**Impact range (80-20)**
Tropical forest reforestation	1.1	0.3	1.0	1.0	0	Yes	Yes	1.33	0.74	1.93	1.19
Tropical forest avoided loss	1.2	0.6	1.0	1.0	0	Yes	Yes	3.80	0.96	7.96	7.00
Temperate forest reforestation	1.3	0.5	1.0	2.0	1	Yes	Yes	1.60	0.73	2.61	1.88
Temperate forest avoided loss	1.4	0.7	1.0	2.0	1	Yes	Yes	0.63	0.15	1.21	1.06
Natural grassland avoided loss	1.5	0.8	1.0	2.2	1.2	Yes	Yes	0.30	0.13	0.59	0.46
Agroforestry	1.6	0.7	1.0	2.0	1	Yes	Yes	1.36	0.19	3.79	3.59
Tropical forest improved management	1.6	0.7	1.0	2.0	1	Yes	Yes	0.98	0.26	1.80	1.54

Mangrove avoided loss	1.6	0.7	1.0	2.0	1	Yes	Yes	0.36	0.00	0.74	0.74
Tropical peatland avoided loss	1.6	0.8	1.0	2.0	1	Yes	Yes	0.29	0.01	0.68	0.67
Temperate forest improved management	1.7	0.7	1.0	2.0	1	Yes	Yes	0.73	0.00	1.73	1.73
Mangrove restoration	1.7	0.5	1.0	2.0	1	Yes	Yes	0.30	0.11	0.70	0.58
Emergent marsh avoided loss	1.8	0.8	1.0	2.4	1.4	Yes	No	0.05	0.01	0.20	0.19
Boreal/temperate peat avoided loss	1.9	0.8	1.0	2.6	1.6	No	No	0.54	0.14	1.10	0.96
Peatland restoration	1.9	0.7	1.0	2.2	1.2	Yes	Yes	0.73	0.20	1.40	1.20
Cropland to perennial veg/crops	2.0	0.9	1.0	3.0	2	Yes	Yes	1.65	0.70	3.50	2.80
Cropland cover cropping	2.0	0.8	1.0	3.0	2	Yes	Yes	0.30	0.20	0.50	0.30
Grassland adjusted stocking	2.1	1.0	1.0	3.0	2	Yes $^{\alpha}$	No	0.20	0.00	0.76	0.76
Emergent marsh restoration	2.1	0.9	1.0	3.0	2	Yes	No	0.07	0.00	0.02	0.02
Cropland biochar amendment	2.2	0.8	1.8	3.0	1.2	Yes	Yes	2.43	0.09	6.52	6.44
Boreal forest improved management	2.2	0.8	1.8	3.0	1.2	Yes	Yes	1.23	0.18	3.08	2.90
Cropland reduced/no till/rotations	2.2	0.8	1.8	3.0	1.2	Yes	Yes	0.33	0.14	0.60	0.46

Grassland restoration	2.2	0.7	2.0	3.0	1	Yes	Yes	1.69	0.68	2.70	2.02
Grassland fire management	2.2	0.8	1.6	3.0	1.4	Yes	No	0.40	0.00	0.65	0.65
Boreal forest avoided loss	2.2	1.0	1.0	3.0	2	Yes	No	0.30	0.10	3.00	2.90
Pasture management (irrigation, legumes [γ])	2.3	0.9	1.4	3.0	1.6	Yes	Yes	0.17	0.02	0.43	0.41
Freshwater wetland avoided loss	2.3	0.9	1.4	3.0	1.6	Yes	No	0.00	0.00	0.01	0.01
Grassland rotational grazing	2.3	0.8	2.0	3.0	1	Yes [α]	Yes	0.20	0.00	0.55	0.55
Boreal forest reforestation	2.4	0.7	2.0	3.0	1	Yes	Yes	0.53	0.00	1.43	1.43
Shrubland avoided loss	2.4	0.8	1.8	3.0	1.2	Yes	Yes	0.20	0.00	0.93	0.93
Cropland compost amendment	2.4	0.9	1.6	3.0	1.4	Yes	Yes	--	--	--	--
Seagrass avoided loss	2.5	0.8	1.8	3.0	1.2	Yes	Yes	0.13	0.04	0.32	0.29
Freshwater wetland restoration	2.6	0.7	2.0	3.0	1	Yes	Yes	0.50	0.00	1.30	1.30
Grassland compost/fertilization	2.6	0.5	2.0	3.0	1	Yes	No	1.15	0.59	1.65	1.07
Macroalgae farming	2.7	0.5	2.0	3.0	1	No	No	0.30	0.00	0.62	0.62
Seagrass restoration	2.8	0.4	2.6	3.0	0.4	Yes	Yes	1.60	0.87	5.73	4.87
Grassland EMW	2.9	0.4	3.0	3.0	0	No [e]	No	--	--	--	--

Ocean avoided benthic disturbance	2.9	0.4	3.0	3.0	0	No	No	--	--	--	--
Cropland EMW	2.9	0.4	3.0	3.0	0	No [e]	Yes[‡]	--	--	--	--
Coral reef restoration	2.9	0.3	3.0	3.0	0	No	No	0.50	0.00	1.30	1.30
Ocean mesopelagic fishing limits	3.0	0.0	3.0	3.0	0	No	No	--	--	--	--
Coral reef avoided loss	3.0	0.0	3.0	3.0	0	No	No	--	--	--	--
Cropland microbial amendments	3.0	0.0	3.0	3.0	0	Yes [β]	Yes	--	--	--	--
Ocean animal biomass restoration	3.0	0.0	3.0	3.0	0	No	No	--	--	--	--

[†] Market activity refers to credits issued under a given protocol and projects that have been registered and initiated by January 2023 but might not yet have resulted in verified carbon credits.
[ψ]Standard deviation is not strictly appropriate in this case, given the bounded distribution, but shown simply for additional information on spread of responses.
[α] Some methodologies do not explicitly list eligible grazing practices but include “prevention of overgrazing” and require monitoring of grazing activities. Other protocols, such as VM0032, say that project activities eligible include any that manipulate number and type of domestic livestock grazing animals and/or grouping, timing, and season of grazing in ways that sequester soil carbon and/or reduce methane emissions.
[β] Most cropland protocols simply say “amendments” and do not specify types.
[γ] Sowing legumes is not explicitly addressed in grassland protocols. Protocols generally include language around reducing bare soil and planting vegetation.
[‡]No protocol yet exists, but there is advance market commitment.
[e] Verra is establishing the Enhanced Weathering and Mineralization Advisory Group (AG) as a resource to support development of an EWM initiative under VCS.

Table 2. Mean categorization of 43 NbCS pathways each of the three categories, standard deviation, and 20th/80th percentiles. "Expert elicitation" is the data from the ten experts (same as SI 3 Table 1); "Expert Elicitation + Monte Carlo" is results including an additional ten draws from the original data distribution; "Differences" is the difference between the original and supplemented data.

Expert Elicitation					**Expert Elicitation + Monte Carlo**					**Differences**				
Category	**mean**	**SD**	**80th**	**20th**	**Category**	**mean**	**SD**	**80th**	**20th**	**Category**	**mean**	**SD**	**80th**	**20th**
Agroforestry	1.6	0.7	2	1	Agroforestry	1.6	0.7	2	1	Agroforestry	0.0	0.0	0	0
Avoided benthic disturbance	2.9	0.4	3	3	Avoided benthic disturbance	2.8	0.4	3	3	Avoided benthic disturbance	0.0	0.0	0	0
Boreal forest avoided loss	2.2	1.0	3	1	Boreal forest avoided loss	2.3	0.8	3	1.6	Boreal forest avoided loss	-0.1	0.2	0	-0.6
Boreal forest improved management	2.2	0.8	3	1.8	Boreal forest improved management	2.0	0.8	3	1	Boreal forest improved management	0.2	0.0	0	0.8
Boreal forest reforestation	2.4	0.7	3	2	Boreal forest reforestation	2.5	0.6	3	2	Boreal forest reforestation	-0.1	0.1	0	0
Boreal/temperate peat avoided loss	1.9	0.8	2.6	1	Boreal/temperate peat avoided loss	2.0	0.8	3	1	Boreal/temperate peat avoided loss	-0.1	0.0	-0.4	0
Coral reef avoided loss	3.0	0.0	3	3	Coral reef avoided loss	3.0	0.0	3	3	Coral reef avoided loss	0.0	0.0	0	0
Coral reef restoration	2.9	0.3	3	3	Coral reef restoration	2.9	0.3	3	3	Coral reef restoration	0.0	0.0	0	0
Cropland biochar amendment	2.2	0.8	3	1.8	Cropland biochar amendment	2.1	0.8	3	1	Cropland biochar amendment	0.1	0.0	0	0.8
Cropland compost amendment	2.4	0.9	3	1.6	Cropland compost amendment	2.4	0.8	3	2	Cropland compost amendment	0.1	0.1	0	-0.4
Cropland cover cropping	2.0	0.8	3	1	Cropland cover cropping	2.0	0.8	3	1	Cropland cover cropping	0.1	0.1	0	0
Cropland EMW	2.9	0.4	3	3	Cropland EMW	2.9	0.3	3	3	Cropland EMW	0.0	0.0	0	0
Cropland microbial amendments	3.0	0.0	3	3	Cropland microbial amendments	3.0	0.0	3	3	Cropland microbial amendments	0.0	0.0	0	0

Cropland reduced/ no till/rotations	2.2	0.8	3	1.8	Cropland reduced/ no till/rotations	2.3	0.8	3	1.8	Cropland reduced/ no till/rotations	0.0	0.0	0	0
Cropland to perennial veg/crops	2.0	0.9	3	1	Cropland to perennial veg/crops	1.9	0.8	3	1	Cropland to perennial veg/crops	0.1	0.1	0	0
Emergent marsh avoided loss	1.8	0.8	2.4	1	Emergent marsh avoided loss	1.8	0.8	2.4	1	Emergent marsh avoided loss	0.0	0.0	0	0
Emergent marsh restoration	2.1	0.9	3	1	Emergent marsh restoration	2.1	0.8	3	1	Emergent marsh restoration	0.1	0.1	0	0
Freshwater wetland avoided loss	2.3	0.9	3	1.4	Freshwater wetland avoided loss	2.3	0.8	3	2	Freshwater wetland avoided loss	-0.1	0.1	0	-0.6
Freshwater wetland restoration	2.6	0.7	3	2	Freshwater wetland restoration	2.6	0.6	3	2	Freshwater wetland restoration	-0.1	0.1	0	0
Grassland compost/fertilization	2.6	0.5	3	2	Grassland compost/fertilization	2.6	0.5	3	2	Grassland compost/fertilization	0.0	0.0	0	0
Grassland EMW	2.9	0.4	3	3	Grassland EMW	2.8	0.4	3	3	Grassland EMW	0.0	0.0	0	0
Grassland fire management	2.2	0.8	3	1.6	Grassland fire management	2.2	0.8	3	1.6	Grassland fire management	0.1	0.1	0	0
Grassland grazing rotation	2.3	0.8	3	2	Grassland grazing rotation	2.3	0.7	3	2	Grassland grazing rotation	0.0	0.1	0	0
Grassland adjusted stocking	2.1	1.0	3	1	Grassland adjusted stocking	2.1	0.9	3	1	Grassland adjusted stocking	0.0	0.1	0	0
Grassland restoration	2.2	0.7	3	2	Grassland restoration	2.2	0.7	3	2	Grassland restoration	0.1	0.0	0	0
Macroalgae farming	2.7	0.5	3	2	Macroalgae farming	2.7	0.5	3	2	Macroalgae farming	-0.1	0.0	0	0
Mangrove avoided loss	1.6	0.7	2	1	Mangrove avoided loss	1.6	0.6	2	1	Mangrove avoided loss	0.0	0.1	0	0
Mangrove restoration	1.7	0.5	2	1	Mangrove restoration	1.7	0.6	2	1	Mangrove restoration	0.0	-0.1	0	0

Natural grassland avoided loss	1.5	0.8	2.2	1	Natural grassland avoided loss	1.3	0.7	1.2	1	Natural grassland avoided loss	0.2	0.2	1	0
Ocean animal biomass restoration	3.0	0.0	3	3	Ocean animal biomass restoration	3.0	0.0	3	3	Ocean animal biomass restoration	0.0	0.0	0	0
Ocean mesopelagic fishing limits	3.0	0.0	3	3	Ocean mesopelagic fishing limits	3.0	0.0	3	3	Ocean mesopelagic fishing limits	0.0	0.0	0	0
Pasture improved management (irrigation, legumes)	2.3	0.9	3	1.4	Pasture improved management (irrigation, legumes)	2.2	0.8	3	1.4	Pasture improved management (irrigation, legumes)	0.1	0.1	0	0
Peatland restoration	1.9	0.7	2.2	1	Peatland restoration	1.8	0.7	2	1	Peatland restoration	0.2	0.0	0.2	0
Seagrass avoided loss	2.5	0.8	3	1.8	Seagrass avoided loss	2.7	0.7	3	2	Seagrass avoided loss	-0.2	0.2	0	-0.2
Seagrass restoration	2.8	0.4	3	2.6	Seagrass restoration	2.6	0.5	3	2	Seagrass restoration	0.1	-0.1	0	0.6
Shrubland avoided loss	2.4	0.8	3	1.8	Shrubland avoided loss	2.4	0.7	3	2	Shrubland avoided loss	0.0	0.1	0	-0.2
Temperate forest avoided loss	1.4	0.7	2	1	Temperate forest avoided loss	1.5	0.7	2	1	Temperate forest avoided loss	-0.1	0.0	0	0
Temperate forest improved management	1.7	0.7	2	1	Temperate forest improved management	1.6	0.6	2	1	Temperate forest improved management	0.2	0.1	0	0
Temperate forest reforestation	1.3	0.5	2	1	Temperate forest reforestation	1.2	0.4	1.2	1	Temperate forest reforestation	0.1	0.1	0.8	0
Tropical forest avoided loss	1.2	0.6	1	1	Tropical forest avoided loss	1.3	0.6	1.2	1	Tropical forest avoided loss	-0.1	0.1	-0.2	0
Tropical forest improved management	1.6	0.7	2	1	Tropical forest improved management	1.7	0.7	2	1	Tropical forest improved management	0.0	0.0	0	0
Tropical forest reforestation	1.1	0.3	1	1	Tropical forest reforestation	1.0	0.2	1	1	Tropical forest reforestation	0.0	0.1	0	0

Tropical peatland avoided loss	1.6	0.8	2	1	Tropical peatland avoided loss	1.7	0.9	3	1	Tropical peatland avoided loss	0.0	0.0	-1	0
										Average differences	0.02	0.05	0.01	0.00
										Average of absolute difference	0.06	0.06	0.08	0.10

Table 3. Means for each of seven sources of uncertainty assigned by experts for NbCS pathways ranked as Category 2. Uncertainty was ranked from 1-5 where 1 was least uncertain and 5 was most uncertain. Means shown for all pathways, uncertainty rankings may vary depending on the number of experts that put the pathway into Category 2 and ranked uncertainty. A blank indicates no ranking. Pathways which were entirely ranked as Cat 1 or 3 were not collected, and so do not appear on the table. For Grassland and Cropland EMW, one expert ranked as Category 2 but did not provide uncertainty rankings.

NbCS pathway	Geography	Mechanism	Scale	Leakage	Measurement	Additionality	Durability
Agroforestry	2.7	2.7	3.0	3.3	3.0	3.0	4.3
Avoided benthic disturbance	2.0	5.0	-	1.0	3.0	4.0	-
Boreal forest avoided loss	-	2.0	-	3.0	1.0	4.0	5.0
Boreal forest management	3.0	1.5	3.3	3.0	2.0	3.3	3.5
Boreal forest reforestation	2.3	3.0	3.0	2.3	4.0	3.0	4.0
Boreal/temperate peat avoided loss	2.5	1.0	2.0	2.5	3.0	4.5	4.3
Coral reef restoration	-	1.0	-	-	3.0	4.0	5.0
Cropland biochar amendment	1.5	3.0	2.0	1.8	4.5	3.7	2.3
Cropland compost amendment	-	2.0	1.0	4.0	5.0	-	3.0
Cropland cover cropping	3.0	1.8	3.0	2.7	4.0	4.0	2.5
Cropland reduced/no till/rotations	3.0	3.0	2.7	5.0	3.3	2.0	3.0
Cropland to perennial veg/crops	2.0	2.0	1.7	3.0	3.7	3.7	3.0
Emergent marsh avoided loss	2.5	1.0	2.5	4.0	4.0	3.3	4.7
Emergent marsh restoration	2.0	1.5	3.5	4.0	-	3.0	4.0
Freshwater wetland avoided loss	1.0	4.5	2.0	2.5	3.0	4.0	1.5
Freshwater wetland restoration	2.0	3.0	1.0	3.0	3.0	3.5	3.0
Grassland compost/fertilization	1.0	2.0	1.0	3.0	4.5	3.0	4.0
Grassland fire management	3.0	2.5	2.7	2.0	4.5	3.5	3.5
Grassland rotational grazing	3.0	2.0	4.0	4.0	4.0	3.0	4.0
Grassland adjusted stocking	1.0	2.0	3.0	4.0	3.0	3.0	1.0
Grassland restoration	2.0	1.8	3.3	2.3	3.0	4.7	4.3
Macroalgae farming	2.0	2.3	1.5	3.0	2.7	2.7	1.7
Mangrove avoided loss	1.5	2.3	2.0	2.7	3.0	3.3	4.3
Mangrove restoration	1.8	1.5	3.7	2.8	2.6	3.5	3.7
Natural grassland avoided loss	3.0	-	5.0	1.0	4.0	2.0	-

Pasture manag. (irrigation, legumes)	3.0	1.0	2.5	2.5	4.0	2.0	5.0
Peatland restoration	1.5	2.2	2.3	2.7	4.0	3.3	3.6
Seagrass avoided loss	3.0	-	4.0	-	5.0	1.0	2.0
Seagrass restoration	2.5	2.0	5.0	4.0	1.5	4.0	5.0
Shrubland avoided loss	2.0	5.0	3.5	1.0	4.0	2.5	2.0
Temperate forest avoided loss	4.0	1.0	1.0	2.0	2.5	2.5	4.0
Temperate forest management	2.7	1.8	3.0	2.4	2.5	3.6	3.6
Temperate forest reforestation	3.0	1.0	1.5	2.0	4.0	3.7	4.3
Tropical forest management	3.0	2.0	2.0	3.0	2.7	3.5	3.3
Tropical forest reforestation	-	1.0	1.0	2.0	4.0	5.0	3.0
Tropical peatland avoided loss	2.0	2.0	2.7	1.7	2.5	2.7	4.3

Table 4. Non-climate benefits identified by experts for each of the 43 NbCS pathways.

Co-benefit	**Frequency**	**Co-benefit**	**Frequency**
Air quality	18	Livestock health	1
Animal health	2	Local cooling	7
Biodiversity	152	Mangrove conservation	2
Bioplastics and biofuels	1	Ocean acidification	6
Cattle foraging efficiency	1	Pollination services	1
Clean water	3	Protecting built structures	5
Coastal human-ecological systems	6	Permafrost	2
Coastal protection	22	Provisioning ecosystem services	9
Control floods	2	Recreation	6
Coral conservation	2	Reduce leaf litter	1
Cultural	3	Reduced fire risk	5
Ecosystem resilience	7	Reduction in cost	1
Erosion	25	Resilience to pests and disease	3
Fisheries	32	Restoration of whaling populations	1
Flood protection	8	Soil health	25
Food production	3	Soil nutrients	28
Food webs	4	Sun penetration	1
Habitat	54	Tourism	4
Improved productivity	18	Water supply	43
Improved water retention	8	Water quality	56
Jobs for local communities	26	Weed reduction	1

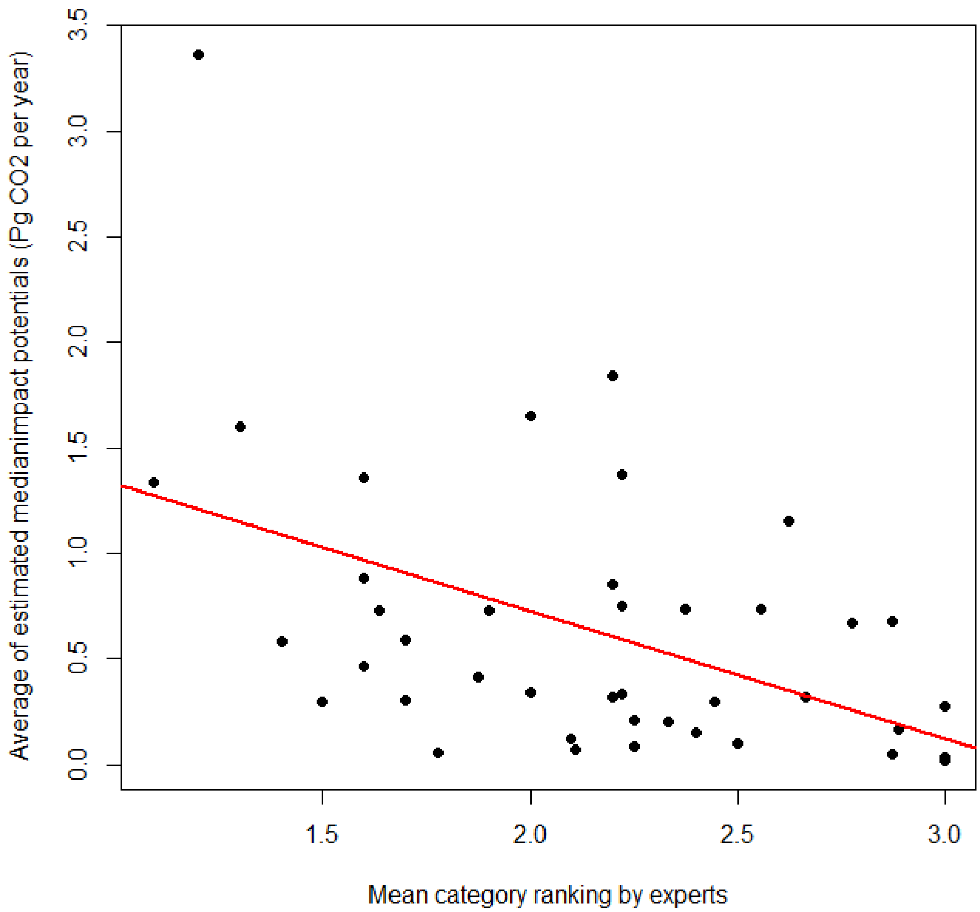


Figure 1. Impact potential compared to confidence categories. As experts rated pathways with increasing uncertainty (e.g., moving from Category 1, with low uncertainty, to Category 3, with high uncertainty), the estimated median impact potential declined. Each point is the mean of a pathway. Trend significant (linear regression: $\beta_{\text{category mean}}$ = -0.60, SE 0.17, r^2 = 0.22), though heavily influenced by the tropical forest avoided loss datapoint (mean category ranking of 1.2 and estimated scale of impact at 3.4). Removing that datapoint reduces the estimated coefficient to -0.40.

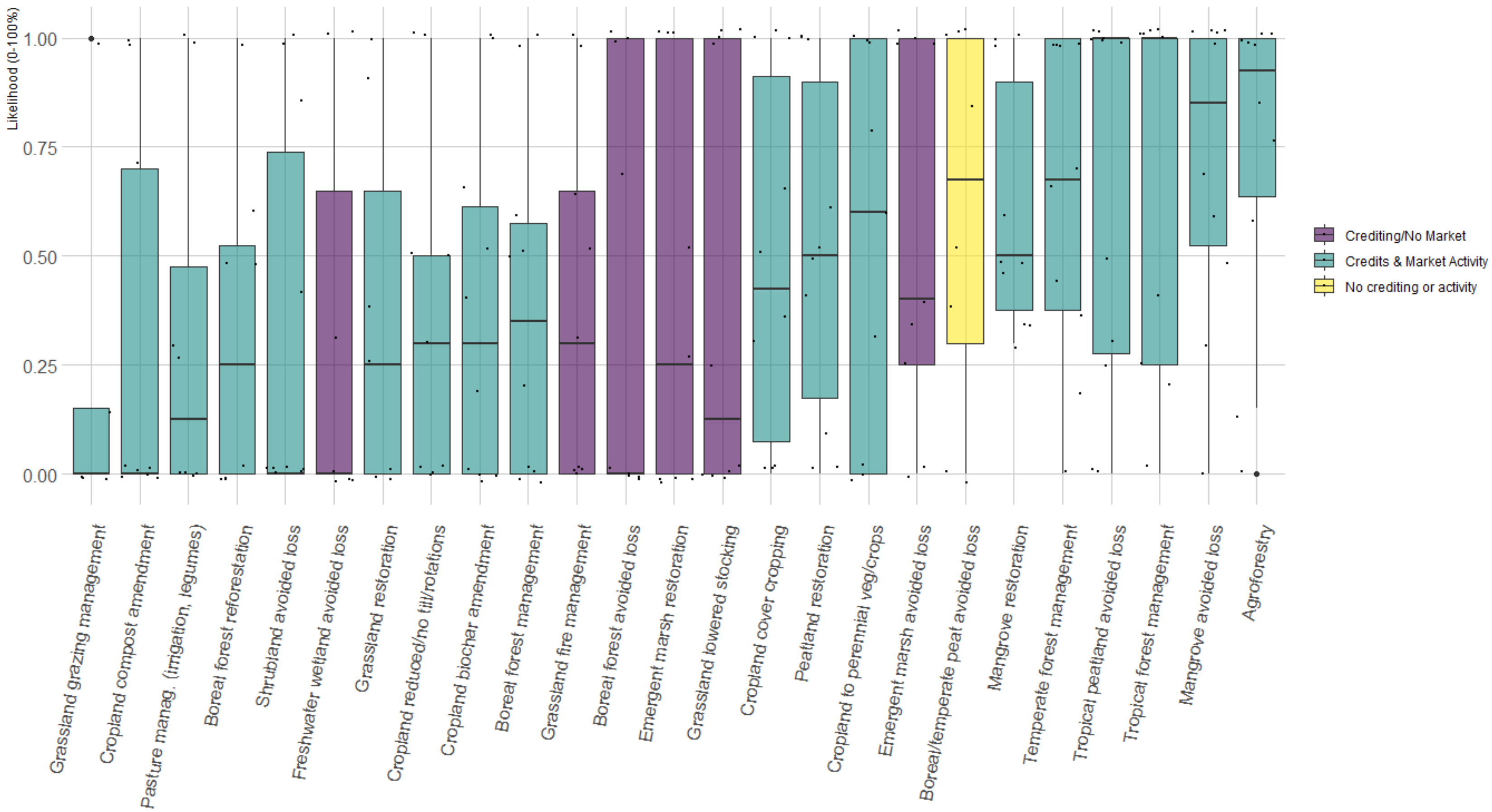


Figure 2. Median estimates (horizontal lines) and 25th/75th percentiles of plausible probability of moving from Category 2 to 1 in the next 3-5 years with intensive research and reasonable funding, colored by carbon crediting or market activity. For responses that ranked the pathway as already Cat 1, a value of 1 (e.g., 100%) was imputed; similarly, for a response that ranked the pathway as Cat 3, a value of 0 (0%) was imputed. Each point is a single response from an expert (slightly jittered to avoid overlap). Only values with mean Category rankings between 1.5 and 2.5 are shown, as the other pathways were either predominantly Cat 1 or Cat 3 already.

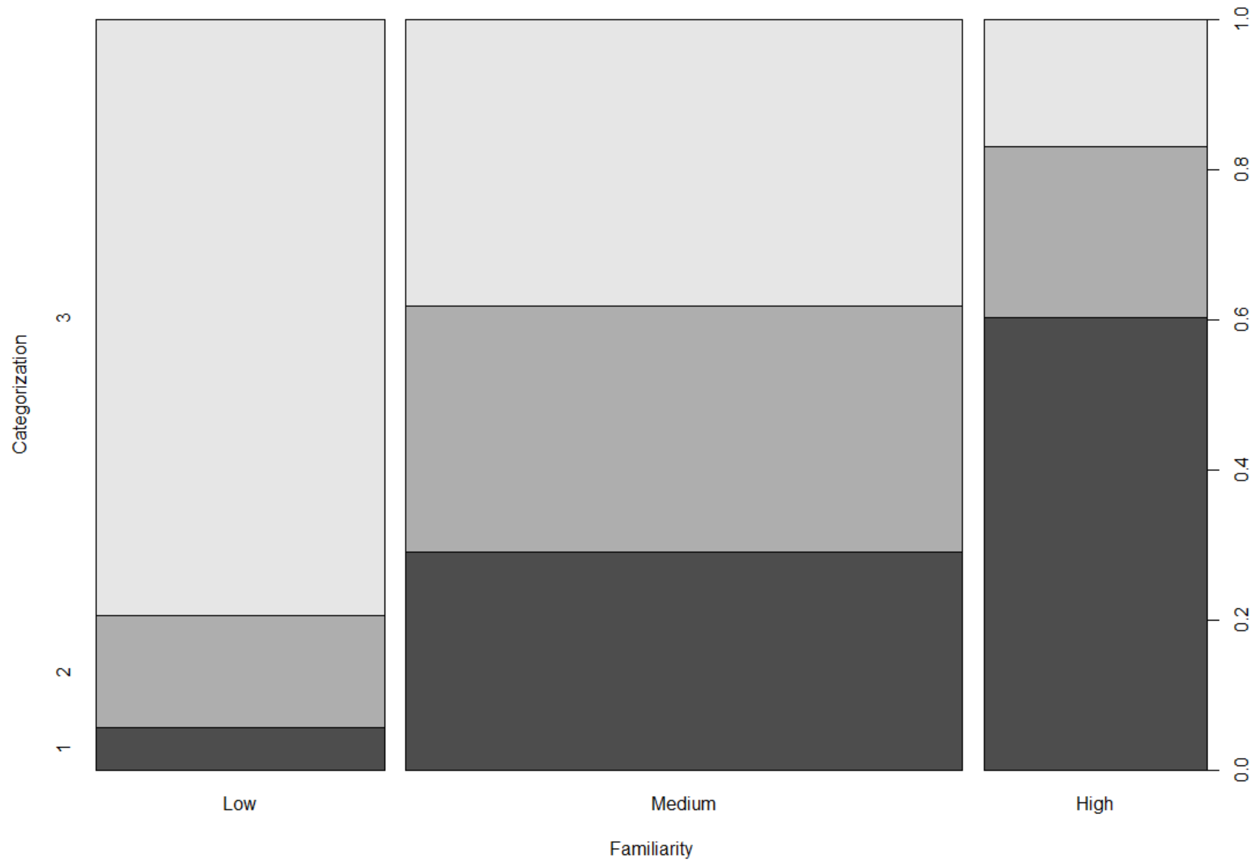


Figure 3. Relationship between familiarity by the experts with a pathway and their categorization of that pathway. The trend of reporting higher uncertainty (e.g., Cat 2 and 3) with lower self-reported familiarity is significant (ordered logistic regression: log odds of 1.8 (1.3-2.4) for stronger categorization for medium familiarity and 3.1 (2.4-3.8) for high familiarity). This suggests a conservative bias of experts to report less confidence in pathways for which they are less familiar.

Supplementary Information: Appendix B

What follows is the final expert elicitation survey. Note that the survey was administered twice, the first as a group calibration/review and the second for actual data collection (per Hemming et al. 2018). This is the second administration, and thus has the occasional reference to the first survey that was inserted to avoid confusion amongst the experts (e.g., "…ordering has changed…"). No data from the first survey was used.

Survey instrument

NCS pathways review: Round 2

Responses will be anonymized. Emails are collected so you have a copy and as a way to record what has been submitted, but will not be released.

* Required

1. Which natural climate solutions (NCS) pathway are you reviewing? *Note: you can do these in any order you would like, they are in no particular order. Please do each one if you can.*

   Mark only one oval.

   1. Tropical forest avoided and reduced deforestation and degradation
   2. Tropical forest reforestation
   3. Tropical forest improved management
   4. Tropical peatland avoided conversion/degradation
   5. Temperate forest avoided conversion/degradation
   6. Temperate forest reforestation
   7. Temperate forest improved management
   8. Boreal forest improved management
   9. Boreal forest reforestation
   10. Grassland lowered livestock stocking rates in overgrazed systems sufficient to increase plant productivity
   11. Grassland avoided degradation and conversion to cropland
   12. Grassland restoration resulting in increased herbaceous biomass on severely degraded grasslands (excluding woody species removal efforts)
   13. Boreal forest avoided conversion/degradation
   14. Shrubland avoided conversion/degradation
   15. Cropland cover cropping
   16. Cropland conversion/restoration of annual crops to perennial vegetation or crops

17. Cropland biochar amendment
18. Cropland microbial amendments
19. Cropland enhanced mineral weathering and microbial amendments
20. Cropland reduced/no till and crop rotations
21. Cropland compost amendment
22. Pasture management (irrigation, sowing legumes)
23. Grassland grazing techniques other than lowering stocking rates (e.g., rotational grazing)
24. Grassland enhanced mineral weathering (EMW) amendments
25. Grassland re management
26. Grassland nutrient addition (compost and fertilizer)
27. Agroforestry
28. Boreal and temperate peatland avoided conversion/degradation
29. Peatland restoration
30. Mangrove avoided conversion and degradation
31. Mangrove restoration
32. Seagrass avoided conversion/degradation
33. Seagrass restoration
34. Emergent marsh avoided conversion/degradation
35. Emergent marsh restoration
36. Freshwater wetland avoided conversion/degradation
37. Freshwater wetland restoration
38. Macroalgae farming
39. Open ocean blue carbon avoided emissions through limits/prohibitions on new shing in mesopelagic zone
40. Avoided open ocean pelagic sediment disturbance (trawling/bottom disturbances)
41. Open ocean blue carbon sequestration via restoration of whales and other large marine animal biomass
42. Coral reef avoided conversion and degradation
43. Coral reef restoration

1. How familiar are you with this NCS in terms of carbon stocks, fluxes, spatial extents, quantification methods, and dynamics?

Mark only one oval.

1. Very familiar
2. Somewhat familiar (e.g., know the basics)
3. Unfamiliar

2. The focus of this study is on whether and to what extent an NCS pathway can support climate change mitigation and overall potential for high quality carbon credit development. However, some NCSs also carry substantial co-benefits, like habitat or storm protection.

If co-benefits could be significant to this pathway, please list up to five.

The goal of this project is to identify whether specific natural climate solution (NCS) pathways have **sufficient scientific basis** for incentivization through financial or other mechanisms. As emphasized, we are not focusing on the economic or social considerations that go into a full crediting system, but rather just the scientific basis of the carbon accounting that must underpin a successful program.

What makes for a high quality carbon system?

- Can we make a robust quantification of the system in a repeatable way? Is that methodology transparent? Do we know the baseline rate of carbon flux and baseline stocks (if applicable) without human intervention, such that we can judge if carbon has been added to the system?
- Are we confident in our understanding of external fluxes of both carbon and other climate-relevant co-factors (e.g., methane releases, N compounds, albedo) such that when we assess the pathway, the estimates of benefits are well constrained, with known/well constrained uncertainty and bias?
- Are we able to confidently assess carbon stability, or quantify risks to that stability with confidence, for approximately 50 years?

We are organizing the project around "bins" that represent, generally, our state of the science understanding of each system with respect to carbon pathways. Certainly, there will always be unknowns at local and regional scales; wherever carbon might be assessed there are idiosyncrasies of place. So rather than focus on if we know every detail for every place, please think about *if we know, and can assess, what we need to know for implementation*. In other words, is the system well understood enough that we can ask the right questions when evaluating carbon stocks and fluxes that might be associated with carbon credits? And can we answer those questions, if we need to? Conversely, do we not yet know how to answer those questions, or even the questions to ask?

Category 1: There is sufficient scientific knowledge to support a high-quality carbon accounting system today, or to support the development of such a system today. This suggests a viable natural solutions pathway to GHG reduction today. We have the knowledge and tools to confidently assess carbon balance and net radiative forcing changes as a result of NCS pathway actions.

Category 2: There is a good chance (>25%) that with more research, and within the next five years, this pathway could be developed into a suitable pathway (Cat 1) for high quality carbon accounting and as a natural climate solution pathway, but before that could happen better understanding will be needed of factors such as baseline processes, long term stability, unconstrained fluxes, possible leakage, etc.

Category 3: This is not much chance (< 25%) that with more research, and within the next five years, this pathway could be developed into a suitable pathway for managing as a natural solutions pathway, either because present evidence already suggests GHG reduction is not likely to be viable, co-emissions or other biophysical feedbacks may offset those gains, or because understanding of key factors is lacking and unlikely to be developed within the next 5 years.

4. Ignoring co-benefits and **considering just GHG mitigation and high-quality carbon system accounting in this pathway,** please indicate the category into which you believe present natural science knowledge allows this pathway to be categorized (see definition above). *

   Mark only one oval.

   - Category 1
   - Category 2
   - Category 3

Uncertainty Category: Descriptions
Per our discussion, the following are the boundaries for the uncertainty categories. You will now be asked to consider these sources of uncertainty for each pathway.

Leakage: This refers to our understanding of spillover effects or displacement of activities (sometimes also called economic leakage). The idea is certainty that NCS actions here do not cause additional actions elsewhere that offset the gains produced by whatever action was taken.

Measurement: This refers to our understanding and ability to quantify the stocks and fluxes of the ecosystem, including any actions taken during or as part of the NCS pathway. Lateral fluxes come in here (e.g., DOC fluxes in groundwater), as do emissions or changes to radiative forcing that may occur as a result of the pathway itself and are not accounted for elsewhere (e.g., transport of macroalgae, production of biochar, etc).

Mechanisms: This refers to our basic understanding of the biophysical system. This includes how well we can constrain models of difficult to measure fluxes, impacts on albedo, co-emissions of other GHG relevant emissions, or any other mechanism resulting from this pathway that impact climate. Think about the systems level knowledge of the science here.

Setting of a Baseline: This refers to the ability to set a cogent baseline for measuring additionality. Per our discussion, this may be conceived of as a "current" baseline or a moving baseline. The choice is yours, and should reflect your opinion what the best available science suggests is the best way to evaluate. This category was previously the additionality category.

Scale of potential: This refers to our ability to confidently scale actions. It is difficult to disentangle this completely from measurement, but is intended to capture uncertainty around boundaries of ecosystems in a spatial or temporal sense. It does NOT refer to the potential for global scale effective action, that is addressed by the Pg per year question at the end.

Durability: This refers to uncertainty involved in pathway due to disturbances or climatic changes which may erode or eliminate any gains by the pathway. Per the discussion, we are generally thinking at a global scale for the pathway, though regionally there may be differences that go into the overall score. As an example, considering global temperate forest pathways, there is uncertainty in global estimates as a result of some areas being more re prone than others. Use your best judgement and available science to make an overall score. This category was previously the stability category.

Geographical variation: This is a new category that resulted from the discussion. There is uncertainty that arises from a lack of geographical distribution in studies or some fundamental factors being less well constrained in some locations vs. others. This category is intended to catch cases where you might think that the other factors are all well known for some regions, but not others, within a category, and that is the major challenge to the pathway overall. For example, there may be a concern about grassland pathways given a preponderance of research in N America but not elsewhere, or in the geographic scale of the biome to which the research applies - this would ag that.

5. **If you ranked this pathway in Category 1 or 3**, please describe remaining uncertainties. *In this question only, you can assign the same uncertainty value to multiple groups.* In the case of Cat 1 pathways, all the uncertainty groups may be considered "low;" in the case of Cat 3 pathways, they may all be high. This new question emerged from our discussion, and is more vague to reflect the fact that many pathways may have low uncertainty across the board, or so high uncertainties as to make ranking and prioritization difficult or impossible.

Mark only one oval per row.

	Low uncertainty	Medium uncertainty	High uncertainty
Durability	◯	◯	◯
Geographical variation	◯	◯	◯
Leakage (displacement of activities, spillover, etc.)	◯	◯	◯
Measurement/ reporting/verification	◯	◯	◯
Mechanisms, including biophysical feedbacks (e.g., albedo) and co-emissions	◯	◯	◯
Other	◯	◯	◯
Scale of potential sequestration potential	◯	◯	◯
Setting of a baseline	◯	◯	◯

If you ranked this pathway in Category 2, please continue to the following items: *An assessment of uncertainty that needs to be resolved prior to moving to Category 1, a sense of the odds associated with resolving that uncertainty, and a sense of costs associated with that effort.*

If you ranked as Cat 1 or Cat 3, you can skip to the end.

There is obvious uncertainty in whether an NCS pathway can be moved from Category 2 to 1, no doubt occurring to you as you completed the assessment above. This question attempts to rank those to determine areas of lowest and highest uncertainty. Please rank the following broad categories, as they relate to this particular pathway, from 1 (low uncertainty, more confident in our understandings/abilities in this area) to 5 (more uncertainty, low confidence in our understandings). The others will fall into the <1 category, as presumably they are the most well known quantities.

This uncertainty refers to uncertainty in our ability to quantify/understand/measure/etc. the process such that you are not confident in ranking it as a Cat 1. **In other words, rank higher levels of uncertainty as higher numbers, and higher numbers are generally intended to be interpreted as stronger reasons why you would rank something Cat 2 vs. Cat 1.** If there is something that is not included here that is highly uncertain, please write it in and score.
*For your 5 main sources of uncertainty - meaning things ranked as 1-5, **please do not rank multiple items at the same score** (e.g., there is only one #1, only one #2, etc). For items which are not a concern for this pathway or for which there is very low uncertainty, you can leave them unranked or rank as <1, and there can be multiple of these. The single ranking from 1 to 5 is important for prioritization setting and discussion purposes.*

Note the order has changed to maintain alphabetical ordering with the new names.
6.

Mark only one oval per row.

	<1, e.g. least concern	1 (less uncertainty)	2	3	4	5 (more uncertainty)
Durability	⬭	⬭	⬭	⬭	⬭	⬭
Geographical variation	⬭	⬭	⬭	⬭	⬭	⬭
Leakage (displacement of activities, spillover, etc.)	⬭	⬭	⬭	⬭	⬭	⬭
Measurement/ reporting/verification	⬭	⬭	⬭	⬭	⬭	⬭
Mechanisms, including biophysical	⬭	⬭	⬭	⬭	⬭	⬭

feedbacks (e.g., albedo) co-emissions						
Other	⬭	⬭	⬭	⬭	⬭	⬭
Scale of potential sequestration potential	⬭	⬭	⬭	⬭	⬭	⬭
Setting of a baseline	⬭	⬭	⬭	⬭	⬭	⬭

1. If you ranked "other" above as one of the top 5, please write what that other issue is here. Otherwise skip this question.

***With focused time and effort, NCS pathways may move up in categories** as research better outlines key constraints, fluxes, and stocks; as models better constrain future trajectories in carbon stocks and fluxes under various expectations of climate change; and/or as research develops better ways to measure net GHG mitigation. They may not.*

Here we want to better define the probability you associated with the Category 2 designation above.

2. Realistically, what do you think is the **lowest plausible possibility** that this pathway will move from Category 2 to Category 1 given three to five years of intensive research (assuming reasonable funding over that time period)? This is your best estimate of the lower end of the 95% confidence interval. (Scale 0-100% in 5% increments).

Mark only one oval.

- 0%
- 5%
- 10%
- 15%
- 20%
- 25%
- 30%
- 35%
- 40%
- 45%
- 50%
- 55%
- 60%
- 65%
- 70%
- 75%
- 80%
- 85%
- 90%
- 95%
- 100%

9. Realistically, what do you think is the **highest plausible possibility** that this pathway will move from Category 2 to Category 1 given three to five years of intensive research (assuming reasonable funding over that time period)? This is your best estimate of the upper end of the 95% confidence interval. (Scale 0-100% in 5% increments).

Mark only one oval.

- 0%
- 5%
- 10%
- 15%
- 20%
- 25%
- 30%
- 35%
- 40%
- 45%
- 50%
- 55%
- 60%
- 65%
- 70%
- 75%
- 80%
- 85%
- 90%
- 95%
- 100%

10. Realistically, what is your best estimate for the **median/most likely probability** that this pathway will move from Category 2 to Category 1 given the same constraints? (Scale 0-100% in 5% increments).

    Mark only one oval.

- 0%
- 5%
- 10%
- 15%
- 20%
- 25%
- 30%
- 35%
- 40%
- 45%
- 50%
- 55%
- 60%
- 65%
- 70%

- 75%
- 80%
- 85%
- 90%
- 95%
- 100%

11. How **confident** are you that your defined range contains the true probability? In other words, a score of 50% means there is even odds your value contains the true probability, a score of 90 or 100% means you are extremely confident your range includes the true probability.

    (The purpose of this question is scaling responses between observers.)

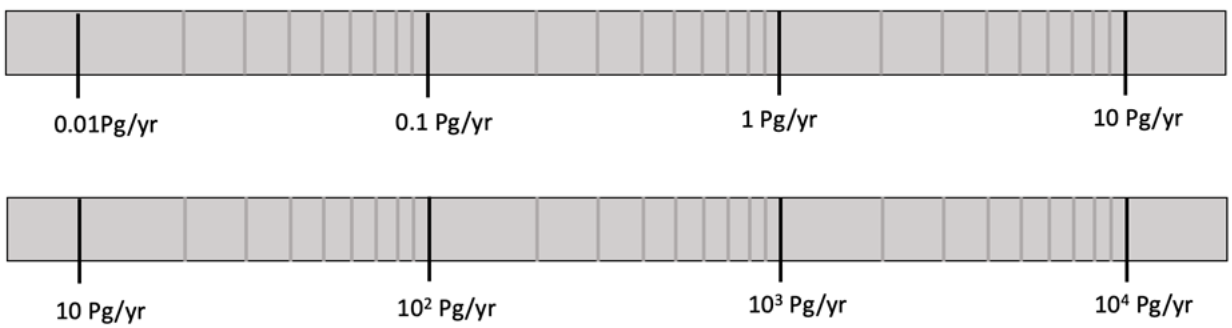
    Mark only one oval.

    - 50%
    - 60%
    - 70%
    - 80%
    - 90%
        - 100%

A second focus of this investigation is on NCS which can have global-scale GHG mitigation impacts. For that we need to estimate the potential scope of impact, inclusive of all additional generated fluxes associated with a pathway (if any).

Please input **numbers only** into the following spaces (for data purposes). If very small, enter <0.01. If very unsure, then enter your best estimate with a large range with low certainty.

You could imagine a scale like this - we're interested in getting the low, high, and median estimates for the effectiveness of this pathway (note the image scales are arbitrarily cut off at 0.01 and 10^4 Pg/yr, no need to constrain yourself to those limits).



1. Realistically, what do you think is the **lowest plausible value for the overall/global scale C sequestration potential (Pg CO2e yr-1)** of this pathway, assuming realistic and feasible adoption levels? This is your best estimate of the lower end of the 95% confidence interval; e.g., there's a 2.5% chance the real value is lower than this.

Please input the number only, assuming units of Pg CO2e yr-1.

2. Realistically, what do you think is the **highest plausible value for the overall/global scale C sequestration potential (Pg CO2e yr-1)** of this pathway, assuming realistic and feasible adoption levels? This is your best estimate of the higher end of the 95% confidence interval; e.g., there's a 2.5% chance the real value is lower than this.

Please input the number only, assuming units of Pg CO2e yr-1.

3. Realistically, what do you think is the **median plausible value for the overall/global scale C sequestration potential (Pg CO2e yr-1)** of this pathway, assuming realistic and feasible adoption levels? This is your best estimate of the median of the 95% confidence interval; e.g., there's a 2.5% chance the real value is lower than this.

Please input the number only, assuming units of Pg CO2e yr-1.

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4. How **confident** are you that your defined range contains the true probability? In other words, a score of 50% means there is even odds your value contains the true probability, a score of 90 or 100% means you are extremely confident your range includes the true probability.

(The purpose of this question is scaling responses between observers.)

Mark only one oval.

2. 50%
3. 60%
4. 70%
5. 80%
6. 90%
7. 100%

Thank you so much for reviewing this pathway!