DRYLAND FORESTATION

Limited climate change mitigation potential through forestation of the vast dryland regions

Shani Rohatyn[1]*, Dan Yakir[2]*, Eyal Rotenberg[2], Yohay Carmel[1]

Forestation of the vast global drylands has been considered a promising climate change mitigation strategy. However, its actual climatic benefits are uncertain because the forests' reduced albedo can produce large warming effects. Using high-resolution spatial analysis of global drylands, we found 448 million hectares suitable for afforestation. This area's carbon sequestration potential until 2100 is 32.3 billion tons of carbon (Gt C), but 22.6 Gt C of that is required to balance albedo effects. The net carbon equivalent would offset ~1% of projected medium-emissions and business-as-usual scenarios over the same period. Focusing forestation only on areas with net cooling effects would use half the area and double the emissions offset. Although such smart forestation is clearly important, its limited climatic benefits reinforce the need to reduce emissions rapidly.

Leveraging the ability of forests to sequester carbon is considered a promising approach to mitigating global climate change (*1*–*3*). Forestation (including afforestation to create new forests and reforestation to restore depleted forests) is also known to cool the local climate by increasing evaporation and inducing increased cloud formation (*4*, *5*). A rich body of scientific research supports tree planting as an effective approach to mitigating global warming. Griscom *et al.* (*2*) calculate that reforestation of ~700 Mha in temperate and tropical zones would result in sequestration of almost three billion tons of carbon per year (Gt C year^{-1}). Bastin *et al.* (*3*) refer to tree restoration as "among the most effective strategies for climate change mitigation." They estimate that reforesting 1700 Mha could potentially sequester 205.7 Gt C (133.2 to 276.2 Gt C) over the lifetime of the forests (*6*).

Trees sequester atmospheric CO_2, and thus planting has a cooling effect by lowering its atmospheric concentration (*7*). Forestation also reduces the reflectance of shortwave radiation (albedo) more than most other forms of land coverage and thus increases net radiation and sensible heat flux, creating local and, potentially, global warming effects (*8*). These contrasting effects have long been recognized (*9*–*11*). However, this warming effect is largely confined to boreal regions. Recognition of this phenomenon is evident in recent publications supporting reforestation as a climate mitigation tool (*2*, *12*), wherein the albedo effect was avoided by excluding the boreal biome from the analysis to obtain maximal climatic benefits. However, there are recent indications that albedo warming effects are also substantial in temperate zones and hot drylands (*13*, *14*). In some dryland regions, the albedo warming effect of afforestation may strongly outweigh the cooling effect of carbon sequestration owing to the change from bright desert land to darker dense forest cover (*15*).

Drylands are defined as having an aridity index (or AI, the ratio between mean annual precipitation and mean annual potential evapotranspiration) of <0.65 (*16*). Drylands cover 40% of the global land area (*17*), with much of their area available for forestation actions. Drylands are also considered potential carbon sinks because of their soil properties and their long turnover time, which suggests that foresting drylands may result in carbon being transferred efficiently from the forest to the underlying dryland soils (*18*, *19*). An analysis of two global restoration opportunities indicated that 50% of global restoration potential is located in drylands (*3*, *20*). Afforestation and reforestation projects in drylands are ongoing around the world, and recently some large-scale projects were initiated or are planned to commence soon in places such as China, the Sahel, and Saudi Arabia (*21*, *22*). Together, these initiatives aim to convert >500 Mha of dryland from nonforested to forested land. However, given that in some regions the net effect of forestation is warming, these large projects may produce unintended climate warming outcomes. A fine-scale, spatially explicit analysis of the contrasting effects of forestation (*23*, *24*) is thus imperative to correctly assess the expected climate-related outcomes of such projects and their cost-effectiveness (*25*). Large-scale afforestation may eliminate rare species that depend on nonforested drylands and may thus have serious consequences for biodiversity (*26*–*29*). Such extinctions may be avoided by limiting afforestation to specific areas within a region, rather than covering the whole available area with forests (*30*, *31*). In any case, biodiversity conservation considerations impose additional constraints that further limit the amount of land available for afforestation.

Given the costs of large-scale forestation, as well as the possible consequences for biodiversity arising from changes in land coverage, it is of utmost importance to produce (i) precise site-specific estimates of the climatic benefits of dryland forestation and (ii) a robust global estimate of the maximum potential contribution of large-scale dryland forestation as a tool to mitigate climatic warming. Consequently, the overarching goal of this study is to conduct a high-resolution spatial analysis to identify drylands with afforestation potential and to evaluate the actual climatic benefits of undertaking global afforestation actions in those areas, including carbon sequestration and albedo effects.

We used suitability analysis based on land-cover and biological criteria to identify potential dryland for afforestation actions involving the conversion of low vegetation to dense forest cover. We examined the potential contribution of afforestation as a climate mitigation approach, including both carbon sequestration and albedo effects, using a combination of remote sensing tools and data-based estimations (for more information, see methods section in the supplementary materials). To widen our purview beyond afforestation, we also used two previously published forest restoration datasets (*3*, *20*) that applied different criteria than those of our study. Both studies allowed tree planting in areas already covered by woody vegetation (densification) and proposed tree planting in areas that were once covered by forests (reforestation). In contrast, our study focused on semiarid areas that were not previously forested (afforestation). We then simulated carbon sequestration and albedo effects for the restoration maps using the same method as for our afforestation map. Finally, we combined the three forestation maps to simulate the maximal climate change mitigation potential attainable from the forestation of global drylands.

The results provide a quantitative assessment of the published suggestions that climate change may be mitigated by foresting the reportedly large nonforested dryland areas. Our high-resolution spatial analysis of the global semiarid and dry subhumid land areas and associated afforestation suitability analysis identified 448 Mha of global drylands as potentially afforestable (Fig. 1A; ~6% of the global dryland area). The remaining dryland area (~94%) was excluded as lacking suitability for afforestation. The excluded areas were urban areas (<1%), water bodies and wetlands (2%), cropland (17%), areas above the tree line (3%), shrubland and forested areas with woody-vegetation coverage

[1]Faculty of Civil and Environmental Engineering, The Technion–Israel Institute of Technology, Haifa 3200003, Israel. [2]Earth and Planetary Sciences, Weizmann Institute of Science, Rehovot 7610001, Israel.
*Corresponding author. Email: shani.rohatyn@gmail.com (S.R.); dan.yakir@weizmann.ac.il (D.Y.)

above our 15% threshold (25%), and arid and hyper-arid land (AI < 0.2) incompatible with tree survival (47%).

We then simulated the effects of afforesting these 448 Mha over a period of 80 years (2020 to 2100; as a conservative forest life span in these regions). For this period, we estimated the net cumulative carbon sequestration potential (ΔSP) of afforestation as 32.3 Gt C. However, the estimated emissions equivalent of shortwave forcing (EESF) associated with the reduced albedo after forestation of previously unforested drylands greatly reduced this potential in climatic terms. Our analysis indicated that 22.6 Gt C should be sequestered over this period to compensate for the EESF arising from albedo effects (relying on productivity and albedo change from nearby forests relative to the state of current vegetation; see methods). Consequently, the net climatic change (calculated as the net equivalent carbon stock change, NESC = ΔSP − EESF) resulting in cooling was equivalent to the sequestration of only 9.7 Gt C until 2100 (Table 1).

The spatial distribution of the climatic effects of our potential dryland afforestation scheme is presented in Fig. 1. We found the effects of afforestation to follow a clear spatial pattern, with negative NESC (i.e., warming effects) at high latitudes and positive NESC (i.e., cooling effects) at lower latitudes. These patterns indicate that afforestation in countries such as South Africa and Australia would result in positive NESC values (Fig. 1, F and G), whereas afforestation in Kazakhstan and Mongolia is likely to result in large negative NESC values (Fig. 1, B and C). Intermediate results are indicated for afforestation in China and the US (Fig. 1, D and E).

We compared the climatic effects of afforestation (in terms of NESC) using data from previous studies to assess the range of the potential effects from afforestation and reforestation schemes. This comparison expands forestation actions from a narrow focus on afforestation to include both reforestation with diverse forest cover and densification of existing forests, based on the reforestation scenarios of Potapov *et al.* (*20*) and Bastin *et al.* (*3*). Considering the full 448 Mha afforestation area proposed in our study (6% of total drylands), the reforestation scenarios of Potapov *et al.* (*20*) and Bastin *et al.* (*3*) covered forestation opportunity areas that were three and four times larger, respectively, than our afforestation area (15 and 25% of total drylands, respectively; Table 1 and figs. S1 to S3). We simulated the estimated cooling and warming effects in the dryland areas proposed in each of those scenarios using the same protocol and over the same 80-year forest life-span period that we applied to our afforestation map (Table 1 and figs. S1 to S3). For comparison between the different scenarios, we calculated the climate change mitigation efficiency as the normalized rate of NESC per unit of forested area. Climate change mitigation efficiency was highest for the Potapov *et al.* (*20*) reforestation scenario [40.2 tons of carbon per hectare (t C ha^{-1})] and lowest for that of Bastin *et al.* (*3*) (16.0 t C ha^{-1}), with our afforestation scenario showing an intermediate efficiency (21.6 t C ha^{-1}) (Table 1).

We also simulated applying a "smart forestation" approach to both scenarios over the 80-year period. The smart forestation analysis excluded locations where our simulations predicted net warming effects (Table 1, NESC < 0; i.e., the red-colored areas in Fig. 1). In our afforestation scheme, application of smart forestation approximately halved the potential afforestation area while nearly doubling the total NESC values and more than tripling the climate change mitigation efficiency as measured by average NESC rates per hectare (Table 1). A large increase in climatic change mitigation efficiency was also found for both the Bastin *et al.* (threefold increase) and Potapov *et al.* (nearly twofold increase) scenarios. Application of smart forestation increased total NESC by factors of 1.8, 1.3, and 1.9 for the present study, Potapov *et al.* (*20*), and Bastin *et al.* (*3*), respectively (Table 1). We used the results from all three smart forestation scenarios to obtain a first approximation of the upper limit to which forestation can potentially mitigate climate change by increasing net carbon sequestration. To that end, we combined the three available mitigation potential scenarios [current study, Potapov *et al.* (*20*), and Bastin *et al.* (*3*)], selecting the maximum per-pixel NESC value over the three scenarios. As expected, this produced the highest total NESC value over the 80-year simulation period (113.6 Gt C), although not the highest climate change mitigation efficiency (Table 1).

We then used the maximum mitigation potential scenario to estimate the maximum potential of forestation to mitigate climatic warming. An examination of forestation initiatives in northern China, the Sahel region of Africa, and the northern Middle East indicated that 25, 44, and 40%, respectively, of

Table 1. Potential climatic effects of three dryland forestation scenarios and their combined application. Values for the net equivalent carbon stock change (NESC) and its components, the net carbon sequestration potential (ΔSP) and the emissions equivalent of shortwave forcing (EESF), where NESC = ΔSP − EESF, are presented for an 80-year forest lifetime, summed (first three columns) and averaged (last three columns) for the entire forested area. For each scenario, results are presented for the total area of potential forestation ("Total") and solely for forestation in areas where it has a cooling effect ("NESC > 0"). The maximum mitigation potential selects the maximum per-pixel NESC over all three forestation scenarios. Carbon sequestration estimates for ΔSP are based on remote sensing and actual flux measurements in the relevant areas (see materials and methods in the supplementary materials).

Forestation scenario	Sum over entire area (Gt C)			Average rates (t C ha^{-1})		
	ΔSP	EESF	NESC	ΔSP	EESF	NESC
Afforestation (current study)						
Total (448 Mha)	32.3	22.6	9.7	72.1	50.5	21.6
NESC > 0 (251 Mha)	27.8	10.1	17.7	110.7	40.1	70.6
Reforestation [Popatov *et al.* (*20*)]						
Total (1134 Mha)	75.9	30.3	45.6	66.9	26.7	40.2
NESC > 0 (836 Mha)	76.5	19.1	57.4	91.5	22.9	68.6
Reforestation [Bastin *et al.* (*3*)]						
Total (1882 Mha)	57.1	27.1	30.0	30.3	14.4	16.0
NESC > 0 (1148 Mha)	65.9	8.0	57.9	57.4	6.9	50.4
Maximum mitigation potential						
NESC maximum (1804 Mha)	143.5	29.9	113.6	79.6	16.6	63.0

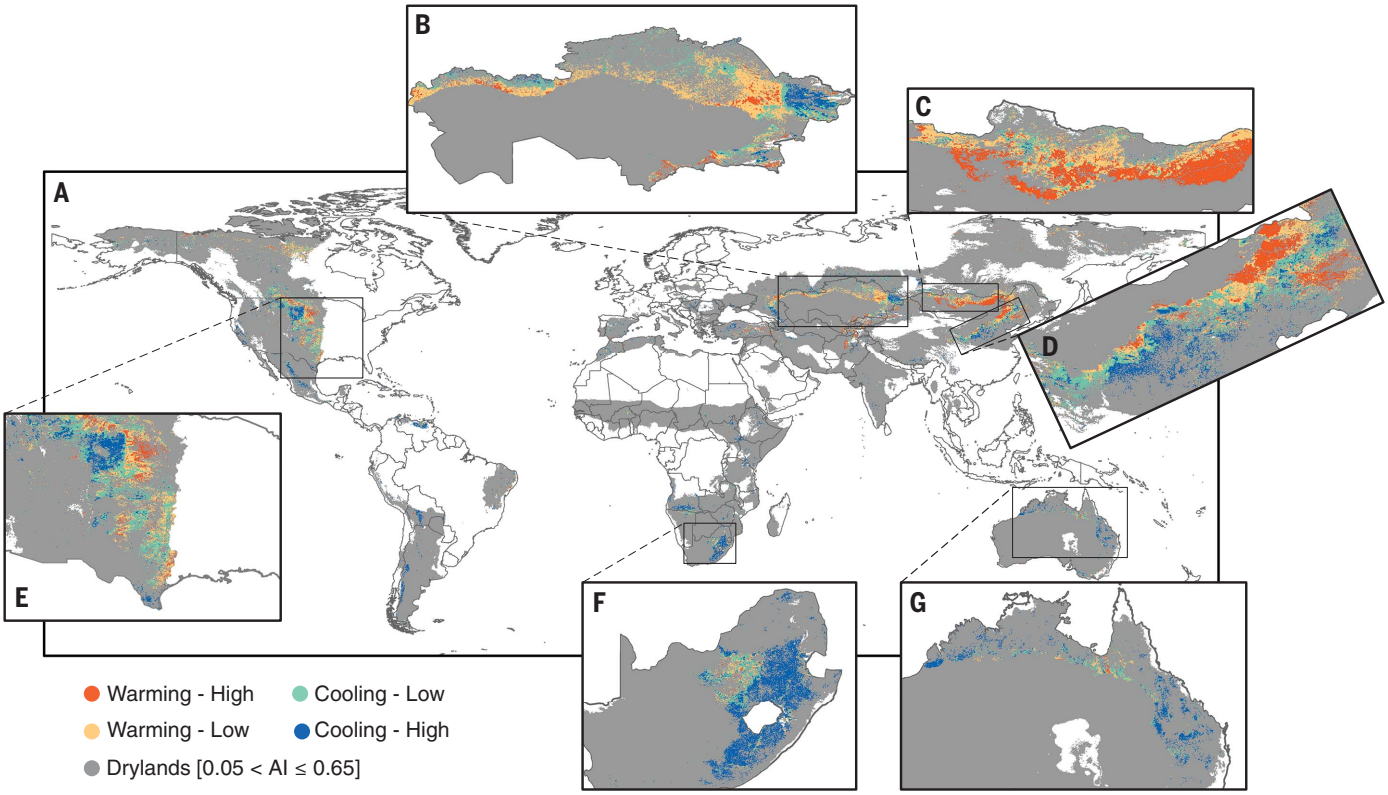

Fig. 1. Net equivalent carbon stock change obtainable from the afforestation of suitable nonforested drylands. (**A** to **G**) NESC outcomes calculated as the net difference between the carbon sequestration potential (ΔSP) and the emissions equivalent of shortwave forcing (EESF) arising from forestation-induced changes in albedo. Colors represent the NESC effect range, where NESC was calculated in units of tons of carbon per hectare over a forest lifetime of 80 years (2020–2100): high warming, NESC ≤ −50; low warming −50 < NESC ≤ 0 (represents a near-neutral climatic effect); low cooling, 0 < NESC ≤ 50; and high cooling, NESC > 50 (represents the largest potential climate cooling effect). The dark gray background indicates the full extent of global drylands [defined as semiarid and dry-subhumid lands within the aridity index (AI) range of 0.05 < AI ≤ 0.65]. (A) Global map. Zoom-ins of drylands in (B) Kazakhstan, (C) Mongolia, (D) northeastern China (Inner Mongolia), (E) USA, (F) South Africa, and (G) Australia. An interactive map of the results can be found here: https://tinyurl.com/mrt4ycha.

Table 2. Potential contribution of dryland forestation to mitigating global CO_2 equivalents of the greenhouse gas emissions by 2100. Estimated global CO_2 equivalents of the greenhouse gas emissions and the proportion of those emissions potentially mitigable by dryland forestation are shown for three possible emissions pathways. The four dryland forestation scenarios are as defined in Table 1 (limited to areas in which they have cooling effects; NESC > 0). The global greenhouse gas emissions predicted for each climate change response are based on the C-ROADS world climate simulator (*34*), accumulated over a forest lifetime of 80 years (2020–2100). The climate change responses considered were: business-as-usual (BAU); intended nationally determined contribution to reducing greenhouse gas emissions, as of September 2015 (INDC); and pledges to control greenhouse gas emissions to limit global warming to 2°C above preindustrial values (2C).

Response to climate change	Global CO_2 equivalent emissions (Gt C)	Proportion (%) of global CO_2 equivalent emissions potentially mitigable by dryland forestation achieved through:			
		Afforestation (current study)	Reforestation [Potapov *et al.* (*20*)]	Reforestation [Bastin *et al.* (*3*)]	Maximum mitigation potential
BAU	2390	0.7	2	2	5
INDC	1592	1.1	4	4	7
2C	608	2.9	9	10	19

the potential forestation lands will still have net climatic warming effects after 80 years of forestation efforts (fig. S4 and table S1). Clearly, forestation planners and decision-makers should consider climatic warming potential when selecting areas for forestation initiatives.

Finally, the contribution that forestation of drylands can potentially make to offsetting CO_2 equivalents of the greenhouse gas emissions by 2100 was estimated for all scenarios, as summarized in Table 2. We used the CO_2 equivalents emissions predicted by the World Climate Simulator (C-ROADS 2015) for a high-emissions scenario [business as usual (BAU)];

a medium-emissions scenario [intended nationally determined contribution (INDC) to reducing greenhouse gas emissions, as of September 2015]; and a low-emissions scenario to limit the global temperature increase to 2°C above preindustrial averages (2C). Surprisingly, given the vast area involved and its considerable carbon uptake potential, the global potential of large-scale dryland forestation to mitigate climate change is relatively poor, which reflects the large EESF in these regions. When considering BAU projections, even the maximum mitigation potential scenario could compensate for just 5% of cumulative emissions over the next 80 years (Table 2). Only under the highly optimistic 2C response (which assumes a reduction in emissions to only 25% of their BAU values) does the proportion of emissions potentially mitigatable by global dryland forestation (involving >20% of the drylands area) rise to nearly a fifth (19%).

It is important to note that forestation, if carefully planned and implemented, may provide local benefits, including soil erosion prevention, recreation, local evaporative cooling, and possibly increased precipitation (*4*, *5*, *32*). Moreover, although our study simulates the net climatic cooling benefits of forestation over an 80-year period, dryland forests may sustain a large carbon sink for a longer time, owing to their large potential soil carbon stock (*18*, *19*), thus providing long-term mitigation of climatic warming.

Previous estimates of the potential to mitigate climatic warming through large-scale forest restoration projects predicted a mitigation effect much larger than the results of this study. Using the restoration opportunities map of Potapov *et al.* (*20*), Griscom *et al.* (*2*) estimated that over an 80-year forest lifetime, the global reforestation of 700 Mha globally (~30% in drylands) could mitigate climatic warming to a maximum of 200 Gt C, which is nearly twice the value we obtained. This translates to a forestation sequestration potential per unit area of ~300 t C ha^{-1} over that period. Similarly, Bastin *et al.* (*3*) estimated a potential carbon stock density of ~200 t C ha^{-1} for the restoration of deserts, xeric shrublands, and Mediterranean forests. Both estimates are considerably higher than those of the present study. These differences likely arise from the additional consideration in the present study of two main factors: (i) the potential sequestration of current vegetation cover before reforestation; and (ii) the warming effect arising from the reduced albedo of forested drylands.

Our results demonstrate the importance of assessments of climatic warming mitigation plans including the warming effect arising from the reduced albedo of global dryland forestation. Accounting for albedo and avoiding foresting drylands where forestation would have a net warming effect (NESC < 0, Table 1) almost doubles the overall expected effect on climate. In contrast, forestation actions over negative-NESC areas would risk exacerbating, rather than ameliorating, global warming. Our analysis does not include additional effects that can further complicate a climate mitigation assessment of forestation, such as climate change–related effects on atmospheric temperature, clouds, or the extent of radiative cooling (from upwelling of long-wave radiation). Such effects influence both productivity and albedo and can move the aridity of some land areas to values outside the forestation suitability range considered here ($0.2 < AI \leq 0.65$) [e.g., (*33*)]. A detailed climate change impact analysis is well beyond the scope of this Report, but for a first approximation, we performed a cross-analysis by superimposing maps of the expected AI in 2100, considering a BAU scenario [+4°C (*33*)] over our forestation map. We found that ~3% of the potential forestation land (~10 Mha) will shift to a drier aridity value, below our minimum AI threshold of 0.2, by 2100. This analysis indicates that future climate change has only minor effects on our estimates of the land available for forestation and does not alter our conclusions.

Here we demonstrate, therefore, that it is critical that forestation opportunities be assessed with respect to their potential to mitigate climatic warming, and that doing so can greatly improve the cooling effect of forestation opportunities (both per-hectare and in terms of total land area used) of forestation opportunities. Forestation efforts, focusing on the limited areas with the potential for net climatic cooling, could benefit from high-resolution (1-km) maps, such as those developed in the present study. Overall, we estimate the total contribution toward offsetting CO_2 emissions obtainable from all dryland forestation actions to be limited, emphasizing the need to reduce emissions rapidly to meet climate targets.

REFERENCES AND NOTES

1. S. L. Lewis, C. E. Wheeler, E. T. A. Mitchard, A. Koch, *Nature* **568**, 25–28 (2019).
2. B. W. Griscom *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **114**, 11645–11650 (2017).
3. J.-F. Bastin *et al.*, *Science* **365**, 76–79 (2019).
4. J. I. Syktus, C. A. McAlpine, *Sci. Rep.* **6**, 29194 (2016).
5. G. Yosef *et al.*, *Sci. Rep.* **8**, 996 (2018).
6. *Science* **368**, eabc8905 (2020).
7. D. A. N. Ussiri, R. Lal, *Carbon Sequestration for Climate Change Mitigation and Adaptation* (Springer International Publishing, 2017).
8. G. B. Bonan, *Science* **320**, 1444–1449 (2008).
9. R. A. Betts, *Nature* **408**, 187–190 (2000).
10. G. Bala *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 6550–6555 (2007).
11. R. G. Anderson *et al.*, *Front. Ecol. Environ.* **9**, 174–182 (2011).
12. S. C. Cook-Patton *et al.*, *Nature* **585**, 545–550 (2020).
13. Q. Zhang *et al.*, *Global Change Biol.* **26**, 3384–3401 (2020).
14. S. Rohatyn, E. Rotenberg, D. Yakir, Y. Carmel, *Environ. Res. Lett.* **16**, 104039 (2021).
15. E. Rotenberg, D. Yakir, *Science* **327**, 451–454 (2010).
16. R. J. Zomer, A. Trabucco, D. A. Bossio, L. V. Verchot, *Agric. Ecosyst. Environ.* **126**, 67–80 (2008).
17. U. Safriel, Z. Adeel, in *Ecosystems and Human Well-Being: Current State and Trends: Findings of the Condition and Trends Working Group*, R. Hassan, R. Scholes, N. Ash, Eds. (Island Press, 2005), pp. 623–662.
18. R. Qubaja, J. M. Grünzweig, E. Rotenberg, D. Yakir, *Global Change Biol.* **26**, 1626–1637 (2020).
19. R. Lal, *Environ. Manage.* **33**, 528–544 (2004).
20. P. Potapov, L. Laestadius, S. Minnemeyer, Global map of forest landscape restoration opportunities (World Resources Institute, 2011); www.wri.org/forest-restoration-atlas.
21. D. Goffner, H. Sinare, L. J. Gordon, *Reg. Environ. Change* **19**, 1417–1428 (2019).
22. L. Laestadius, K. Buckingham, S. Maginnis, C. Saint-Laurent, *Unasylva* **66**, 11–18 (2015).
23. R. A. Betts, *Nat. Geosci.* **4**, 504–505 (2011).
24. V. K. Arora, A. Montenegro, *Nat. Geosci.* **4**, 514–518 (2011).
25. S. Cao *et al.*, *Earth Sci. Rev.* **104**, 240–245 (2011).
26. K. D. Holl, P. H. S. Brancalion, *Science* **368**, 580–581 (2020).
27. J. W. Veldman *et al.*, *Bioscience* **65**, 1011–1018 (2015).
28. W. J. Bond, N. Stevens, G. F. Midgley, C. E. R. Lehmann, *Trends Ecol. Evol.* **34**, 963–965 (2019).
29. A. F. Souza, N. P. Ramos, M. A. Pizo, I. Hübel, L. O. Crossetti, *J. Nat. Conserv.* **21**, 56–62 (2013).
30. S. Gómez-González, R. Ochoa-Hueso, J. G. Pausas, *Science* **368**, 1439 (2020).
31. Y. Choi *et al.*, *Biol. Conserv.* **267**, 109474 (2022).
32. I. Stavi, *Forests* **10**, 737 (2019).
33. A. G. Koutroulis, *Sci. Total Environ.* **655**, 482–511 (2019).
34. T. Fiddaman, L. S. Siegel, E. Sawin, A. P. Jones, J. Sterman, C-ROADS Simulator Reference Guide (2019).

ACKNOWLEDGMENTS

S.R. was supported by scholarships from the Technion–Israel Institute of Technology and the Weizmann Institute of Science. The authors thank A. Smadi for help with data collection and processing, R. Chemke for code optimization, and A. Singer-Lavi for important comments on an earlier draft. **Funding:** This project was supported in part by the Blumenstein Family Information Center at GWRI, the Technion–Israel Institute of Technology (ISF 1976/17 to D.Y.); a Minerva Foundation grant (to D.Y.); and the Yotam project and the Weizmann Institute Sustainability and Energy Research Initiative (SAERI P134470 to D.Y.). **Author contributions:** All authors jointly planned and designed the research. S.R. analyzed the data, and all authors interpreted the results. S.R. wrote the original draft, and all authors contributed substantially to revisions. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** The data that support the findings of this study were all derived from resources available in the public domain (see table S2 for descriptive information on the datasets). Data corresponding to the results reported here are available in the supplementary materials (data S1 to S3).

SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.abm9684
Materials and Methods
Figs. S1 to S5
Tables S1 and S2
References (*35*–*53*)
Data S1 to S3

Submitted 31 January 2022; accepted 23 August 2022
10.1126/science.abm9684

Science

Limited climate change mitigation potential through forestation of the vast dryland regions

Shani RohatynDan YakirEyal RotenbergYohay Carmel

Science, 377 (6613), • DOI: 10.1126/science.abm9684

Just a little help

Forestation of the global drylands has been suggested to be a way to decrease global warming, but how much promise does it actually have? Rohatyn *et al*. found that the climatic benefits are minor. Although drylands have considerable carbon sequestration potential, which could be used to lower the amount of carbon dioxide in the atmosphere and thereby slow warming, the reduction of albedo caused by forestation would counteract most of that effect. So, although forestation is clearly important, it cannot substitute for reducing emissions. —HJS