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Different types of drought under climate change or geoengineering: Systematic review of societal implications

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Climate change and solar geoengineering have different implications for drought. Climate change can "speed up" the hydrological cycle, but it causesgreater evapotranspiration than the historical climate because of higher temperatures. Solar geoengineering (stratospheric aerosol injection), on the other hand, tends to "slow down" the hydrological cycle while reducing potential evapotranspiration. There are two common definitions of drought that take this into account; rainfall-only (SPI) and potential-evapotranspiration (SPEI). In different regions of Africa, this can result in different versions of droughts for each scenario, with drier rainfall (SPI) droughts under geoengineering and drier potential-evapotranspiration (SPEI) droughts under climate change. However, the societal implications of these different types of drought are not clear. We present a systematic review of all papers comparing the relationship between real-world outcomes (streamflow, vegetation, and agricultural yields) with these two definitions of drought in Africa. We also correlate the two drought definitions (SPI and SPEI) with historical vegetation conditions across the continent. We find that potential-evapotranspiration-droughts (SPEI) tend to be more closely related with vegetation conditions, while rainfall-droughts (SPI) tend to be more closely related with streamflows across Africa. In many regions, adaptation plans are likely to be affected differently by these two drought types. In parts of East Africa and coastal West Africa, geoengineering could exacerbate both types of drought, which has implications for current investments in water infrastructure. The reverse is true in parts of Southern Africa. In the Sahel, sectors more sensitive to rainfall-drought (SPI), such as reservoir management, could see reduced water availability under solar geoengineering, while sectors more sensitive to potential-evapotranspiration-drought (SPEI), such as rainfed agriculture, could see increased water availability under solar geoengineering. Given that the implications of climate change and solar geoengineering futures are different in different regions and also for different sectors, we recommend that deliberations on solar geoengineering include the widest possible representation of stakeholders.

KEYWORDS

climate change, geoengineering, drought, SPI, SPEI, Africa, streamflow, NDVI

Introduction

Drought is one of the most complex climate-related hazards to define, because of the myriad of different ways in which lack of water can manifest in different climate zones and in relation to different societal needs. With climate change, different regions of the world are expected to see increasing or decreasing amounts of total annual precipitation, with a general trend toward "speeding up" the hydrological cycle, because a warmer atmosphere can hold more water and cause more precipitation (IPCC, 2021). However, a warmer atmosphere could ultimately result in less water availability, even in some places with increasing total precipitation, due to increased evaporation rates and dry spells (Haile et al., 2020; Naik and Abiodun, 2020; Oguntunde et al., 2020).

Under scenarios of solar geoengineering, in which humans block a portion of incoming sunlight to cool the planet, future temperatures are not as high as in climate change scenarios. In turn, the hydrological cycle also slows down, and models project that a geoengineering scenario that fully reduces anthropogenic warming would cause a decrease in total precipitation in many regions compared to today's climate (Cheng et al., 2019; Simpson et al., 2019). To avoid problems caused by slowing down the hydrological cycle, Irvine et al. (2019) investigate the outcomes of a strategy that uses solar geoengineering to halve the global temperature increase, as compared to a complete offset of climate change induced temperature increase. Their results indicate that there is less of a drying effect for much of the world in this scenario, using potential evapotranspiration as a measure. While not necessarily the "ideal" level of geoengineering, this proposal is a more appropriate option if the intention is to avoid the type of reversing of climate processes that occurs when complete offset parameterization is used, and several other studies have also investigated ways of partially offsetting temperature changes (Kravitz et al., 2014; Lee et al., 2020).

While the calculations involved with managing the appropriate amount of incoming solar radiation are already complex from a geophysical perspective, the definition of "sufficient management" must also include the impact on and feedback from socioeconomic variables. In short, people must clearly be part of the equation. There are the possibilities of experiencing benefits from geoengineering, such as cooler temperatures, a more stable climate, and increasing the ability of humans to manage planetary boundary level interactions related to acidification and improving the efficiency of soil carbon management (Sovacool, 2021). The cost of addressing climate change with geoengineering either as a primary or complementary mechanism has been noted to be more cost effective than non-geoengineering related mitigation strategies. While benefits can be achieved, estimating the uncertainties in regional impacts can be difficult to quantify given traditional approaches, with the risk of large scale global systems failure if either processes are not designed proposal and/or governance structures do not function as planned (Caldeira et al., 2013; Gardiner and Fragnière, 2018).

Given the complexity of these projections, the implications for rainfall and temperature under a future with climate change or with solar geoengineering are complex, involving a spatially-varying mix of changes to temperature and precipitation. For Africa, Abiodun et al. (2021) found that climate change is projected to decrease water availability due to increasing evaporation, while geoengineering would mitigate the increase in evaporation but also decrease total precipitation in many regions. However, it is not clear what these results mean for human systems, for example, to know whether existing water management plans will be affected by the two different scenarios. Here, we carry out a systematic review of how the different types of droughts under climate change or geoengineering might relate to societal outcomes.

One of the most commonly-used drought definitions is the Standardized Precipitation Index (SPI), as proposed by McKee et al. (1993). SPI is a simple way to compare the extremity of rainfall deficits across regions and different timescales. The only input to SPI is total precipitation on a particular timescale, with 1 month through to 24 months being common temporal units of analysis.

Almost 20 years later, Vicente-Serrano et al. proposed a related drought definition, the Standardized Precipitation Evapotranspiration Index (SPEI), which would take into account the importance of potential evapotranspiration (PET) for water availability (Vicente-Serrano et al., 2010). This index is calculated in a similar way to the SPI, but using PET as an input. PET can be estimated through multiple methods depending on data availability ranging from simple temperature and solar radiation based estimates such as Hargreaves (Hargreaves and Samani, 1985), or more complex methods such as Penman-Monteith which includes wind speed and humidity. The rationale behind this drought definition was partly to be able to measure the importance of increasing temperatures with climate change on water availability (Vicente-Serrano et al., 2010). Importantly, SPEI integrates *potential* or reference evapotranspiration which assumes essentially unrestricted moisture availability at the surface. In most cases this will be larger than actual evaporation. SPEI therefore represents the upper limit of potential moisture deficit.

When compared to a preindustrial climate, projections of climate change in Africa tend to include increases in extreme droughts as defined by SPEI, because of the inclusion of increasing temperatures which drive increases in PET. On the other hand projections of the impact of solar geoengineering tend to include more extreme droughts as defined by SPI, which only uses rainfall (Abiodun et al., 2021).

In many regions of the world, there is little difference between SPI and SPEI variability, as demonstrated in analyses of their historical record. This is particularly true in non-arid regions, where drought is driven mostly by rainfall variability (Fuentes et al., 2022). However, in a world with high temperature increases due to climate change, these two drought definitions might diverge further, as PET might play a larger role in some regions (Noureldeen et al., 2020). Unfortunately, large uncertainties in observational data of temperature and precipitation limit our understanding of these two types of droughts, because the choice of input data in some regions of the world can have a greater impact on drought estimates than the choice of how drought is defined in the first place (Hoffmann et al., 2020).

In this article, we seek to advance progress in understanding the spectrum of potential societal implications of various future drought scenarios through a comparison of projections under a scenario of climate change (generally more intense SPEI droughts) and a scenario of solar geoengineering (generally more intense SPI droughts) in Africa.Given that climate change and solar geoengineering would affect drought risk differently in different regions of Africa, we identify how outcomes could be different for different stakeholders across the continent. First, we carry out a systematic literature review to identify which societal outcomes are more sensitive to rainfall-only drought (SPI) or rainfall-and-potential-evapotranspiration drought (SPEI). We then review which regions within Africa are projected to see more frequent droughts under each definition, and discuss implications for common agriculture and water-related adaptation investments on the continent.

Methods

To identify which societal outcomes are more sensitive to SPI or SPEI, we carry out a systematic literature review of all studies comparing these two drought definitions in Africa. First, we searched Web of Science for all papers that include both the terms SPI, SPEI, as well as either the word “Africa” or the name of an African country. This returned 58 peer-reviewed journal articles.

Next, we screened each article to identify whether the paper correlated the SPI and SPEI datasets with a societal outcome variable. Variables included vegetation indices, crop yields, reservoir levels, and stream flows. Papers were not included if they simply correlated SPI and SPEI with each other or other rainfall-derived drought definitions. Papers were also excluded if they presented only correlations for one of the drought indices with societal outcome variables, without presenting results for the other index in order to compare the two. Twelve (12) articles were included in the final dataset. Here we present the results for each study on SPI, SPEI, and societal outcomes.

To complement the literature review, we carried out a global cross correlation of SPI and SPEI with a vegetation index based on the Normalized Difference Vegetation Index (NDVI). The calculation of SPI was done by aggregating monthly rainfall from the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS version 2.0) dataset (Funk et al., 2015) and applying a gamma distribution to the data as suggested by Stagge et al. (2015). SPEI calculation was applied using monthly rainfall from CHIRPS and reference evapotranspiration calculated using the Food and Agriculture Organization (FAO) Penman Monteith equation (Pereira et al., 2015). Reference evapotranspiration was estimated by combining monthly temperatures, wind and surface pressure data from the European Center for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) dataset (Hoffmann et al., 2019) and monthly incoming shortwave radiation from the Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS; McNally et al., 2017). Then, SPEI was calculated using the log-logistic distribution as in (Vicente-Serrano et al., 2010; Vicente-Serrano and Beguería, 2016).

The NDVI monthly data was derived by combining data from the third generation Global Inventory Modeling and Mapping Studies (GIMMS) from the Advanced Very High Resolution Radiometer (AVHRR; Pinzon and Tucker, 2014) and from the Moderate Resolution Imaging Spectroradiometer (MODIS; Didan, 2015). MODIS NDVI was resampled and harmonized to the GIMMS NDVI resolution using ordinary least square regression between datasets (Mao et al., 2012). The standardization of NDVI was applied based on the calculation of z-scores as originally proposed by Peters et al. (2002).

Then, the cross correlation between standardized indices was applied at each pixel. However, the different time series were previously prewhitened using an Autoregressive Integrated Moving Average (ARIMA) model to remove serial correlation (Fuentes et al., 2022). Thus, this analysis was applied to calculate the maximum correlation between lags of 0 and 24 months.

TABLE 1 Results of systematic literature review, which yielded 12 papers satisfying the criteria.

Overview	Citation	Variable	SPI correlation	SPEI correlation
Streamflow				
Little difference between the correlations of SPI or SPEI with streamflow in the Volta River basin.	Oguntunde et al., 2017	Streamflow	Wavelet analysis, see paper	
SPI and SPEI showed weak relationships with hydrological drought in the Niger South basin, not meaningfully different from each other.	Oloruntade et al., 2017	Streamflow	0.05	0.08
The streamflow drought index for Olifants Basin, South Africa, has slightly higher correlation with SPI than SPEI.	Gyamfi et al., 2019	Streamflow	**0.73**	0.63
Niger River Basin streamflow showed higher correlation with SPI than SPEI.	Oguntunde et al., 2018	Streamflow	**0.80**	0.60
Compared to streamflow on two stations of the Blue Nile, SPI had higher correlations than SPEI.	Bayissa et al., 2018	Streamflow (two stations)	**0.55** **0.36**	0.36 0.24
Agricultural yields				
In West Africa, both SPI and SPEI are correlated with crop yield, with small differences in correlations between metrics and crops.	Noureldeen et al., 2020	Sorghum	**0.71**	0.65
		Millet	0.61	**0.72**
		Maize	**0.81**	0.65
In South Africa, both SPI and SPEI are correlated with maize yield, with small differences in correlations in different maize-producing regions.	Adisa et al., 2019	Maize in:		
		Kwazulu-natal	**0.67**	0.47
		Mpumalanga	0.56	0.58
		Free state	0.51	**0.62**
		North west	0.53	**0.69**
Of 11 crops analyzed in Mozambique, SPEI tended to have slightly higher correlations with yields than SPI, but not for all crops.	Araneda-Cabrera et al., 2021	Crop yields	Data presented in figures, see paper	
SPI and SPEI have similar correlations (within 0.05 of each other) with agricultural and hydrological drought indicators at different lags in the Limpopo River basin.	Trambauer et al., 2014	Root stress anomaly index	0.79	0.80
Vegetation				
Both SPI and SPEI are correlated with the vegetation condition index in East Africa, with minimal differences.	Kalisa et al., 2021	Vegetation condition index	0.51	0.46
Different biomes have different correlations between SPI/SPEI and vegetation. Using model data, authors find that historically, correlations between SPEI and vegetation are higher than SPI and vegetation in most biomes, but in the future with climate change, correlations with SPI are projected to strengthen to approach the levels of SPEI.	Lawal et al., 2019b	Vegetation index	Data presented in figures, see paper	
In most regions of Southern Africa, both SPI and SPEI have similar correlations with vegetation conditions. SPEI (Hargreaves method) has slightly higher correlations than SPI with vegetation conditions in Namibia and northern Botswana.	Lawal et al., 2019a	Vegetation index	Spatial map of correlations, see paper	

In cases where multiple time aggregations or time lags were tested, we present the highest correlation that was found. Correlations in bold are at least 0.05 higher than the correlation of the other drought metric.

To contextualize the analysis of societal outcomes, we reproduce here the results from Abiodun et al. (2021), which depict the geographic distribution of changes to SPI and SPEI across Africa under a strong climate change scenario and a specific scenario solar geoengineering that fully offsets global temperature increases due to climate change. When we refer to "solar geoengineering," we are referring specifically to stratospheric aerosol injection.

Results

To understand possible societal consequences of SPI droughts (only rainfall) compared to SPEI droughts (potential evapotranspiration), we present the results of the systematic literature review. Of the 58 papers that included the terms SPI and SPEI in Africa, only 12 showed results that correlated both SPI and SPEI with an outcome variable.

There were three main types of outcomes investigated in these papers: streamflow, agricultural yields, and vegetation. In the studies correlating SPI and SPEI with streamflow, SPI (rainfall only) often had a higher correlation than SPEI (potential evapotranspiration). These studies included two basins in West Africa (Volta and Niger), the Blue Nile in East Africa, and the Olifants Basin in South Africa (Table 1).

The four papers relating SPI and SPEI to agricultural yields found differing results, with each drought indicator showing stronger relationships to different crops or in different regions. Most of these differences in correlations were not strong (e.g., within 0.05 of each other), and therefore do not indicate that one drought definition is better linked to crop yields. See Table 1 for details of each study.

In studies that examined the correlation between the drought definitions and vegetation conditions, results were spatially variable, but more consistent than for agricultural yields. In many regions, researchers found that SPEI had higher correlations with vegetation indices (NDVI) than correlations between SPI and NDVI. Because agricultural yields are influenced by irrigation and other factors, it stands to reason that crop yields could respond less consistently to drought indicators than the unmediated response of rainfed vegetation.

To confirm the results from this literature review, we carry out a global cross correlation of SPI and SPEI with the Standardized Vegetation Index (based on NDVI), once these series were prewhitened (see Methods section). Results are depicted in Figure 1, demonstrating the highest correlation between drought and vegetation at any time lag of 0–24 months. In these historical datasets, SPEI demonstrates higher correlations with vegetation in many parts of the world, especially in dry climate zones, including parts of East Africa, Southern Africa, and the Sahel. SPI and SPEI are highly correlated with each other in many tropical or wet regions of the world, and therefore show smaller differences in terms of correlation with outcome variables in those regions.

Discussion

Different regions of Africa have different projections for SPI (rainfall) droughts and SPEI (potential evapotranspiration) droughts under different scenarios of climate change and geoengineering. Abiodun et al. (2021) examined projections of climate change using a single climate model, the Community Earth System Model (CESM1) with 20 ensemble members under the RCP 8.5 scenario, and compared this with a scenario of solar geoengineering from the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project. In this experiment the stratospheric injection rate is calculated to maintain the global mean temperature as well as the inter-hemispheric and equator-to-pole near-surface temperatures at the 2020 level until the end of the century while keeping other forcing as in the RCP 8.5 scenario. This is a very high emissions scenario. Figure 2 is a reproduction of their results, depicting regions of Africa that could see increasing or decreasing frequency of drought as defined by SPI or SPEI under the two future scenarios. Adaptation investments in each region are likely to see a different set of trade-offs under each scenario.

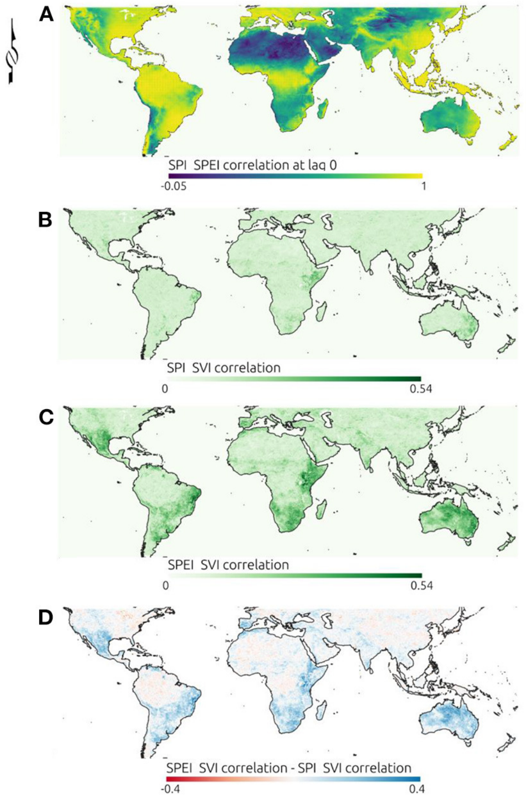

FIGURE 1
Correlations **(A)** between SPI and SPEI; **(B)** between SPI and vegetation conditions, and **(C)** between SPEI and vegetation conditions. **(B,C)** correspond to the maximum correlation at each pixel for a 0-month to a 24-month time lag between prewhitened SPI/SPEI and the prewhitened vegetation condition response. **(D)** The difference between the two correlations: the SPEI correlation minus the SPI correlation.

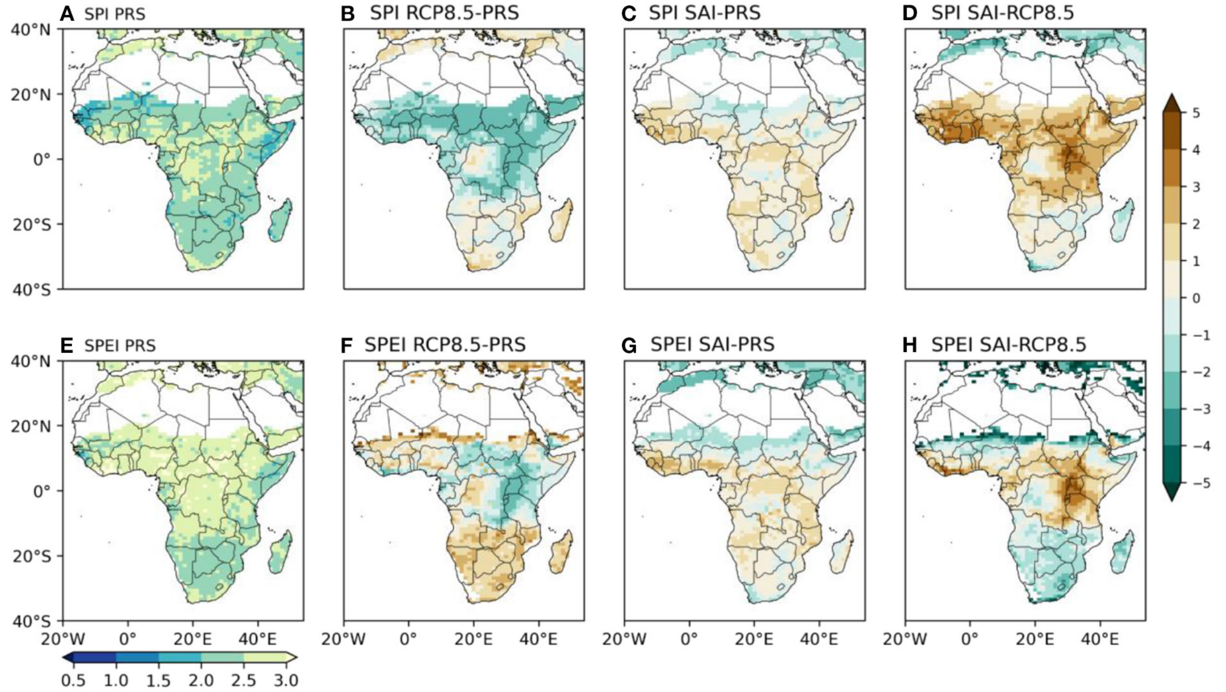

FIGURE 2
Frequency of drought occurrence per decade. The top row shows droughts as defined by SPI (water only), while the bottom row shows droughts as defined by SPEI (including potential evapotranspiration). The leftmost column **(A,E)** depicts the present-day frequency of droughts, the next column shows the change in frequency of SPI **(B)** and SPEI **(F)** droughts under solar geoengineering, compared to present. The third column shows the change in frequency of SPI **(C)** and SPEI **(G)** droughts between solar geoengineering and climate change. The last column **(D,H)** shows the difference between the solar geoengineering scenario and the climate change scenario. Data from Abiodun et al. (2021).

In parts of East Africa and coastal west Africa, this scenario of solar geoengineering (maintaining global temperature) is projected to cause an increase in drought compared to climate change, regardless of which drought definition is used. In these regions, the increase of rainfall due to climate change overcomes the increase in evaporation from temperature increases, so the RCP 8.5 projections are for wetting of SPI and SPEI, while geoengineering is for drying of SPI and SPEI.

In other regions, the drought definition matters. In the Sahel, climate change is projected to make SPI (precipitation) droughts wetter, but make SPEI (potential evapotranspiration) droughts drier. Under the solar geoengineering scenario, these two trends are reversed, with projections indicating a wetter SPEI and drier SPI. In this case, communities reliant on streamflow for flood recession agriculture or irrigation (e.g., Sall et al., 2020) could face water problems in a geoengineered climate under less rainfall, as could those reliant on wetlands for grazing during the dry season (e.g., Adams, 1993). Extending beyond SPI, it is worth considering how climate change and solar geoengineering could affect the seasonality of river flows, with there being robust evidence of a change in flood timing with decadal climate variability (Ficchì and Stephens, 2019).

It is worth noting that the latitude at which aerosols are injected can affect the Inter-tropical Convergence Zone, which is a main influence on rainfall in the Sahel and many other regions. Other designs of solar geoengineering, other than the one explored here, could have different consequences for these regions (Krishnamohan and Bala, 2022).

Lastly, there are several regions in which the solar geoengineering scenario reduces drought relative to the climate change scenario, regardless of which drought definition is used. In Southern Africa, for example, projections for SPI (rainfall) droughts under climate change and geoengineering are similar, but projections for SPEI (potential evapotranspiration) droughts are drier under climate change.

In all regions, people are managing their current climate and preparing adaptations for future changes (Caretta et al., 2022). Table 2 lists several of the water-related adaptation measures that have been documented as climate change adaptation efforts in Africa (Williams et al., 2021). These are categorized into three groups: adaptations related to food and ecosystems that are likely sensitive to SPEI (potential evapotranspiration), and those that are related to water supply management, which are likely sensitive to SPI (rainfall amounts). The two possible future scenarios of climate change and solar geoengineering

TABLE 2 Examples of climate change adaptations in Africa as documented in Williams et al. (2021), which are likely sensitive to differences in future scenarios in which SPI and SPEI change.

Adaptations related to food: many would be sensitive to evaporation (SPEI)
Agroforestry
Sustainable agricultural practice
Agricultural intensification
Crop management
Livestock management
Adaptations related to ecosystems: many would be sensitive to evaporation (SPEI)
Ecosystem restoration and conservation
Ecosystem governance and planning
Adaptations related to water: sensitive to rainfall amounts (SPI)
Alternative water supply
Bulk water infrastructure
Integrated water management
Water governance and planning
Resilient infrastructure and technologies (including flood infrastructure)

are likely to have different implications for the success of these adaptation investments.

In parts of East Africa and coastal West Africa, adaptation investments which intend to address the risk of a wetter climate under climate change may be less useful in a future with solar geoengineering. In these regions, models project an increase in the frequency of droughts, in both SPEI and SPI, that may occur under geoengineering in regions that otherwise would not experience such change. Some communities and ecosystems could be negatively affected, and tradeoffs need to be studied and properly addressed before considering implementation. This is particularly the case for longer-term adaptation investments, such as infrastructure investments, which will last many decades and operate during future scenarios of climate change or geoengineering. To estimate how outcomes might vary over time, further research is needed on the relationships between decadal variability, longer term climate change, and solar geoengineering. Adaptation actions that are robust to projected increases or decreases in water availability over time might be favored.

In the Sahel, water management adaptations in sectors sensitive to SPEI, such as vegetation and agriculture, could see an improvement in drought outcomes under solar geoengineering, as this geoengineering scenario is wetter than the climate change scenario. However, people working in streamflow management, such as construction of dams, reservoirs, and irrigation, or promoting flood recession agriculture as an adaptation strategy (e.g., Sidibe et al., 2016) could see an exacerbation of drought conditions under geoengineering, because these sectors are likely more sensitive to the total precipitation amount, measured by SPI.

Conclusion

The implications of solar geoengineering relative to climate change are not uniform, and they differ by region and sector. Within Africa, there are regions in which both scenarios exacerbate droughts, regions where both future scenarios reduce droughts, and scenarios where climate change and geoengineering cause different types of droughts. Regional differences include places that might benefit easily from the outcomes of geoengineering, and other regions that might need to adjust their development plans if geoengineering is implemented.

These different types of droughts are likely to have different societal implications. Vegetation is likely most sensitive to drought defined as potential evapotranspiration, while streamflows are likely most sensitive to drought defined purely by precipitation amounts. Therefore, different futures in which rainfall (SPI) droughts or potential evapotranspiration (SPEI) droughts are more or less frequent has implications for current adaptation planning. This is particularly relevant for regions that are investing in water management infrastructure for the coming decades.

The projections for specific regions that are described here should be interpreted with caution, due to several sources of uncertainty in how this might play out in the future. First, the societal implications of drought are based on historical analyses, and this relationship between drought and outcomes could change under future scenarios as climate regimes and technologies change. Second, the climate projections here are derived from single models, and a larger multi-model ensemble might offer a wider range of possibilities. Third, the scenarios used here were extreme versions of climate change (RCP 8.5) and solar geoengineering (full offset of global temperature increase), and policy choices could select less dramatic pathways for our future. Lastly, the implementation of geoengineering could be done in different ways; we present results only from the GLENS scenario, which is only one representation of possible aerosol injections. Potentially affected populations should be at the table in discussions of geoengineering governance, because different scenarios will affect them differently.

The outcomes of "drought" are also not limited to climate trends alone. Streamflows, agriculture, and vegetation are also sensitive to non-climate factors, such as land-use change or excessive water extraction. For example, a study in Lake Chilwa Basin, Malawi concluded that rising temperatures were not able to explain declining lake levels, as neither timeseries of SPI nor SPEI related to the declining lake levels (Kambombe et al., 2021). The authors speculated that land use change and other human activities were likely the dominant factors.

Given that SPI and SPEI droughts might affect crops, vegetation, and streamflow differently in different regions under different climate futures, it is dangerous to make broad generalizations that climate change or geoengineering would result in only winners or losers. Rather, scientists and practitioners need to acknowledge the full space of uncertainty about how these climate futures might affect different industries, and ensure that all voices are at the table when discussing research and deployment around solar geoengineering, given the wide variety of possible outcomes and ways in which people could be affected.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

EC designed the study, carried out the literature review, and drafted the article. IP analyzed the geoengineering data and created Figure 2. IF analyzed the SPI/SPEI/NDVI data and created Figure 1. CJ, ES, and AK provided inputs to the study design and text of the article. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Publisher's note

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