warming in the Southern Hemisphere oceans, compared to the Northern, in what might be a reorganization of the entire Hadley circulation[7]. Subsequent studies have parsed the effect of global SST anomalies into regional components, whose path of influence over the Sahel is easier to discern in a mechanistic way. Warming in the tropics — in the Eastern Pacific[8] during an El Niño event and especially, over longer time scales, in the Indian Ocean[4,9] — increases temperatures in the free troposphere across the tropics, which stabilizes the atmosphere and inhibits convection over Africa[10]. The extratropical North Atlantic might influence the Sahel via the Sahara, as anomalously humid and warm air advected from a warm ocean increases regional sea-level pressure gradients and the monsoon flow[11]. Finally, warming in the tropical or subtropical North Atlantic[10,12] or the Mediterranean[1,2] would moisten the monsoon flow and the Harmattan (the northeasterly trade wind from the Sahara), that converge from the west and the northeast into the Sahel — providing more fuel and less inhibition for convection and supporting heavier rainfall. Greenhouse gases (GHGs) can also influence surface temperature and energy fluxes over the continent directly[13], and models uniformly respond to increased atmospheric concentration with a wetting of the Sahel[13]. The issue, however, is that these paths of influence carry different weight in different models[14] and might not add up linearly[5,13].

Park and colleagues suggest that such non-linearity is what has allowed the Mediterranean to become a dominant player in Sahel rainfall variability in recent decades,

as the warm West Pacific has saturated the influence of tropical variability, leaving extratropical influence to dominate. But, by the same token, non-linearity complicates the task of stacking the influence of single forcings against each other and determining which one is dominant: a forcing-by-forcing decomposition assumes that the response to a given forcing 'all else being equal' is the same even when all else is not equal. In simulations by Park and colleagues, the precipitation response to tropical and extratropical SSTs do not neatly add up to the response to the global SST, complicating the interpretation of their results.

Moreover, although it is clear that a colder (warmer) Mediterranean consistently makes the simulations drier (wetter) in the Sahel in the early (late) decades (Fig. 1a), including the Mediterranean forcing does not necessarily make the model match the observations more convincingly[1]. Indeed, the simulated wetting of the last decade exceeds observations. A similar problem had marred the specular claim of a previous study[15], namely that the recovery is all due to GHGs and not at all to the SST. Rising concentrations of GHGs during the last decades does indeed produce additional wetting, but it does not substantially alter how well the models match observations (Fig. 1b). Focusing on only one number, the trend, misses important information, including the apparent and worrisome increase in year-to-year variability[12]; focusing on only one aspect of a complex forcing gives rise to contradictory results, by suggesting that a particular mechanism is dominant, when no such signal has yet emerged.

In solving the mystery of Sahel rainfall, we might have to give up the satisfactory simplicity of a game of Cluedo — one culprit, one weapon — for the complex drama of a film noir. But Park and colleagues[1] have shown us that we had overlooked a suspect: the warming of the Mediterranean will likely be playing an important role in the next decades. Their results make our understanding of the possible outcomes for Sahel rainfall more complete. ❏

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VEGETATION PRODUCTIVITY

Humans did it

Observed vegetation change in the Northern Hemisphere can, with a high degree of confidence, be attributed to human-caused global change.

Robert Buitenwerf

During the past three decades, the vegetation over vast areas of the Northern Hemisphere has been changing. That, in short, is the conclusion from a host of studies using satellite measurements. These studies have found changes that include 'greening' trends, increased plant productivity[1] and earlier starts to the growing season[2]. The detected changes are consistent with what might be expected from global change, including

climate change, elevated atmospheric CO_2, nitrogen deposition and land cover change. For example, the rapid warming of Arctic regions may enable shrubs to replace herbaceous plants and consequently increase productivity[3]. Hence, not only have studies correlated vegetation change to global change, there are also well-known physiological and ecological mechanisms through which global change might be expected to force the observed vegetation

changes. It may come as a surprise then that direct attribution of vegetation change to global change has proved challenging. Writing in *Nature Climate Change*, Mao *et al.*[4] go some way to filling this gap with a cleverly conceived study that combines mechanistic modelling, experiments and observational data.

The difficulty with attributing vegetation change to global change is that the different mechanisms of change are often correlated

(for example, warming and elevated CO_2 concentrations), and they furthermore often have interactive effects on plant growth. Elevated CO_2 concentrations may make plants more efficient in their water use, which can extend the growing season, but concurrent warming can also extend the growing season[5]. This kind of complexity is difficult to account for in statistical analyses of observational data. Traditionally, field or laboratory experiments have been the go-to tool for understanding complex systems, but although experiments have provided invaluable insights in global change science, they are inevitably location-specific, that is, restricted to specific combinations of environmental conditions and taxa. In addition, when dealing with long-lived organisms such as trees, it may simply take too long to acquire relevant data.

A fruitful approach to understanding large-scale changes is to use mechanistic models that simulate important aspects of the system[6]. Such models are used to simulate how the different components of the Earth system, including the atmosphere and biosphere, interact. These Earth system models provide the opportunity to conduct experiments in which a potential driver of vegetation change can be varied while all other potential drivers are kept constant. Comparing the simulated outcome to observed data can then be used as a test of the importance of a driver.

Mao et al. have taken exactly this approach. They employed the best available mechanistic methods, in the form of an ensemble of modern Earth system models, to conduct an experiment on the impact of various scenarios on all vegetation north of 30° N. Some simulations included processes through which humans can affect the Earth system (anthropogenic forcings) such as greenhouse gas emissions, nitrogen deposition and land-use change. Others only included natural climate variability. They then compared the simulated vegetation growth under each scenario to satellite derived observations of vegetation state over the past 30 years. Their findings were clear: simulations with anthropogenic forcings can reproduce the observed record, whereas runs without anthropogenic forcings cannot. Simulations with anthropogenic forcings match the increasing global trend, but to a lesser degree also reproduce the observed spatial patterns of regional increases and decreases. This is solid evidence in support of human-induced climate change affecting vegetation greenness throughout the extratropical Northern Hemisphere.

The authors note several limitations of their study including sources of uncertainty in current Earth system models and

potential issues in the observational record and with the experimental design. Two additional challenges, not treated in this study, can be added.

First, the response variable in this study is the leaf area index (LAI) during the growing season. LAI is the amount of leaf area per ground area and is thus positively related to plant productivity. However, it is also related to the structure of the vegetation — a forest can achieve a higher LAI than a grassland. Without closer inspection it is not possible to know if increases in LAI reflect increased productivity of existing vegetation or if the composition of plant communities has changed[7]. Ecologically these are fundamentally different processes that could have distinct implications for biodiversity and ecosystem functioning, and will also affect feedbacks of vegetation to the Earth system by affecting variables such as albedo that can dampen or amplify future climate change. Ultimately, improved predictive ability of vegetation dynamics will need to move beyond greening and 'vegetation vigour' and address potential changes in vegetation composition (for example, using hyperspectral data) and structure (for example, by using radar and LiDAR).

Second, it remains unclear what is happening south of 30° N, an area that accounts for more than half the global land surface (excluding Antarctica) and around three quarters of the world's above-ground carbon[8]. Unlike the extratropical Northern Hemisphere, plant growth in the tropics is far less seasonal and plant growth in seasonal regions of the Southern Hemisphere is, for the most part, interrupted by a dry rather than a cold season. Another recent study[9] detected LAI increases in these regions too, but it is unclear if such greening is simply a signal of more vigorous growth from existing

vegetation, whether some species have become more dominant at the expense of others, or whether vegetation structure changed more drastically, for example, because woody species replace herbaceous species. Now that the drivers of vegetation change are becoming clear, attention can be directed to understanding the ecological and biogeochemical consequences of anthropogenic vegetation change. ❑

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