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WATER CYCLE RESTORATION PERSPECTIVE FOR THE SINAI

Assessment of natural water production at arid landscapes

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Assessment of natural water production at arid landscapes

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Abstract- *Climate change is often linked to greenhouse gas emissions, but land use change plays an equally critical role. Widespread deforestation and agricultural expansion have undermined the biosphere's ability to regulate climate through evapotranspiration, albedo, and energy exchange. Vegetation is central to maintaining water and energy cycles, with up to 70% of terrestrial precipitation originating from land-based evaporation. When vegetation is lost, this cycle weakens, threatening both freshwater availability and climate stability. Addressing climate change effectively requires moving beyond a carbon-centric perspective to include land restoration and ecosystem dynamics as key strategies for reactivating the climate-regulating functions of the biosphere.*

Afforestation can enhance terrestrial precipitation by increasing atmospheric humidity and reinforcing local moisture recycling, as seen on China's Loess Plateau. Vegetation-driven processes like evapotranspiration support cloud formation, although they may reduce water yield. The biotic pump theory proposes vegetation-driven atmospheric motion, yet the mechanisms of moisture transport remain debated. Small-scale processes—often missed by global climate models—are critical. Advancing afforestation as a climate strategy requires interdisciplinary research, improved observations, and integrated modelling to ensure positive regional water and climate outcomes.

Index Terms- water cycle restoration, land-atmospheric interactions, atmospheric moisture recycling, atmospheric boundary layer, arid land restoration, atmospheric modelling

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I. INTRODUCTION

For the past 6 years, Wetsus and The Weather Makers have been collaborating to better understand the concept of water cycle restoration. Wetsus, the European centre of excellence for sustainable water technology, develops water technology innovations that enable a sustainable future (www.wetsus.eu). The research at Wetsus is organised in several research themes. The theme "Natural Water Production" (NWP-theme) aims at better understanding water cycle restoration and developing water technology that enables water cycle restoration.

Within the NWP-theme the fields of meteorology, hydrology, ecology and mechanical engineering are integrated. We approach the research from a meteorology and hydrology perspective to study the underlying processes of rainfall enhancement and the return of evaporated water as rainfall to land, an ecology perspective to design strategies to obtain a natural water cycle driven by evaporation from vegetation, and a mechanical engineering perspective to develop water technologies that enable water cycle restoration in arid regions.

The main principle that is under development in the NWP-theme is technology enhanced atmospheric moistening for more precipitation. Water technology can be used to efficiently evaporate seawater in coastal regions. If done strategically, this evaporated water may return as rainfall over land within the region and contribute to freshwater availability.

This document describes the different research activities that have been conducted in the NWP-theme at Wetsus and their results. Furthermore, it discusses the implications of these results and future research objectives and plans.

II. DYNAMICS BETWEEN LAND COVER AND CLIMATE

On a planetary scale, anthropogenic forcing has led to a persistent imbalance in the global mean top-of-atmosphere radiation budget (Forster et al., 2021). Perturbations in the radiation budget alters the global mean temperature, rainfall patterns and climate extremes (IPCC, 2022). The burning of fossil fuels and subsequent rising CO_2 levels as the main cause of climate change has become conventional wisdom among scientists and policy makers, and has led to a carbon focus for climate mitigation strategies all over the globe. However, the exclusive focus on greenhouse gas (GHG) emissions as the only cause of climate change has distracted us from another major climate-impacting development that has occurred synchronously, namely land use change. Over the past 10,000 years, but particularly the past 3,000 years, we have altered vast areas of terrestrial surfaces by clearing forests and expanding agriculture (Ellis, 2021), enough to degrade up to 40% of Earth's surface, according to the UNCCD (UNCCD, 2022). This has greatly altered the capacity of the land surface to infiltrate/retain rainfall, protect soils from solar radiation/erosion and contribute to the water/energy cycles via evapotranspiration and cloud formation (Anthes, 1984; Lawrence et al., 2022; Seneviratne et al., 2010). Whilst recognizing CO_2 emissions should be cut back, devising all climate change solutions within the carbon math paradigm will likely fall short in the long term. The state of the climate is not only a function of GHG, but also of water and radiant energy. These are biologically-mediated, interrelated cycles, and deploying only carbon-sequestering technology or reduction strategies will not restore the natural climate-regulating capacity of the biosphere.

A. The climate regulating role of the biosphere

The biosphere includes all life on Earth. The different components of the biosphere have co-evolved with the land, atmosphere and oceans and together govern the state of the climate through regulating the carbon, water and radiant energy cycles (Gettelman & Rood, 2016). This includes a climate in which life on Earth (including humans) has evolved and continue to depend on for their existence. The physical and ecological processes of the biosphere are driven by the energy from the Sun. Incident solar energy that reaches Earth's atmosphere (insolation) will either reflect back to space (depending on clouds, aerosols or atmospheric composition), be absorbed by the atmosphere or penetrate through and reach Earth's surface directly. After which this radiation is reflected or absorbed depending on albedo, which is determined by the colour/texture of the land surface (Spellman, 2017). Upon absorption at the surface, solar energy undergoes a transformation in which biosphere largely governs the flux of energy between the surface and the atmosphere (Gerten et al., 2004). In particular, the biosphere plays an important role in the partitioning of latent and sensible heat (the Bowen ratio), which determines the amount of evapotranspiration and the temperature at the surface (Moon et al., 2020).

Evapotranspiration refers to the process by which water moves from Earth's surface to the atmosphere through soil evaporation and plant transpiration. Globally this process consumes more than half of the incoming radiant energy (Trenberth et al., 2009). Vegetation is the primary factor affecting evapotranspiration, as 59% of global evapotranspiration comes from terrestrial plant transpiration (Wang-Erlandsson et al., 2014). These exchanges and interactions between the biosphere and atmosphere regulate the hydrological cycle, govern the heat dynamics of the Earth and together produce the climate patterns we know today (te Wierik et al., 2021).

Land-atmospheric interactions in the form of water and energy exchanges occur at the atmospheric boundary layer (ABL), which marks the interface between these two spheres and largely influence global weather and climate patterns (Santanello et al., 2018). Changes in land surface affect its roughness properties, which, in turn, govern the degree of albedo and evapotranspiration coming from it (Perugini et al., 2017). Changes in evapotranspiration mediate the energy and water balance of the atmosphere and can influence local and regional climate and temperature (Wang-Erlandsson et al., 2022). For example, changes in vegetal biomass – particularly in regions with high Vegetation-regulated Moisture Recycling (VMR) – can have critical effects on the amount downwind precipitation (Keys et al., 2016).

The combined effects of land cover changes thus have widespread implications for weather and climate dynamics (Anthes, 1984). The myriad effects from land cover change often have opposing signs in radiative forcing, making their combined feedbacks critical for understanding the net climate impact (Bright et al., 2015). Integrating all the physical effects of land degradation and restoration remains a challenge. Site-specific atmosphere–biosphere interactions and feedbacks should be considered with respect to their local and global impacts. Efforts to regain losses in structure and functioning of land surfaces must take on a predictive and proactive approach, based on an understanding of the local water cycle and the root causes of degradation, and a recognition of the nonstationary nature and uncertainty of climate trends (Milly et al., 2008).

The forcing and feedback from changes in the sensible heat flux due to the degradation of the biosphere has been hidden in the shadow of the dominant CO_2/GHG narrative. Studies show that land cover changes and the resultant energy balance perturbations have had significant impacts on the global water cycle (Wang-Erlandsson et al., 2022) and the atmospheric energy budget (Duveiller et al., 2018). For example, land use change is a dominant contributor to global-mean temperature and precipitation change through alterations of the latent and sensible heat fluxes (Mahmood et al., 2013; Perugini et al., 2017) as well as a driver in changing climate extremes (Sy & Quesada, 2020). The regional and global effects of landscape conversion are inherently location-dependent (Mahmood et al., 2013), and there is still a high level of uncertainty in quantifying these effects (Perugini et al., 2017). As such, we must avoid basing actions entirely on generalised statements on the benefits or drawbacks of re- or afforestation, but rather on site-specific research that reveals the coupling between ecosystem dynamics and global climate feedbacks (Mahmood et al., 2013).

B. Atmospheric moisture recycling and terrestrial precipitation

Freshwater scarcity is one of humanity's most pressing issues, which has not only left billions without adequate access to drinking water, but also threatens our global food security and heightens the risk of social conflicts and increases the spread of diseases (Gleick & Cooley, 2021). Precipitation is the only sustainable fresh water source that exists and thus the promotion of precipitation across terrestrial surfaces is crucial towards ensuring reliable access to freshwater. There is no 'one-size-fits-all' approach to enhance precipitation on land because of the heterogeneity of surface conditions such as orography, distance to coast and mean insolation. Precipitation is, however, a function of a number of distinct factors that can be leveraged in order to produce the environmental conditions for precipitation to occur, one of which is evaporation (Anthes, 1984).

In the past, biogeographers generally assumed that local precipitation is an external variable that is not influenced by vegetation (van Noordwijk & Ellison, 2019), but an increasing number of studies have now proven this assumption to be incorrect (Alton et al., 2009; Ellison et al., 2017; Gong et al., 2017; Keys et al., 2017; Makarieva et al., 2013; Millán et al., 2005; Savenije, 1995, 1996; te Wierik et al., 2021; van der Ent et al., 2010; Wang-Erlandsson et al., 2014). The mechanistic role of vegetation reduction on drought spells (Savenije, 1995) and the role that terrestrial vegetation plays in transporting moisture from oceanic origin land inwards (Keys et al., 2016; Makarieva et al., 2013) are two highly relevant findings that may be the key to restoring rainfall.

A ‘precipitation shed’ describes spatial origin of moisture (where it has evaporated from) that falls as rain in a specific location (van der Ent et al., 2010). An understanding of the origin of moisture opens up opportunities to improve governance of the global distribution of water, but also allows for strategic action towards water cycle regeneration. In continental catchments moist airmasses (‘sea breeze’) are formed over water bodies and travel across terrestrial surfaces, the added moisture through evapotranspiration from land acts as a trigger component that is required for condensation and precipitation to occur (Millán, 2014a). Evapotranspiration has thus been shown to be the most important mechanism in sustaining rainfall over land surfaces (Savenije, 1996), due to the cascading effects of moisture moving inland (Schaefli et al., 2012). The loss of evapotranspiration through land degradation is thus a direct threat towards the establishment of predictable rainfall in many regions.

Terrestrial moisture recycling is an important concept that refers to the process by which moisture evaporates from land and returns to land surfaces via precipitation. It has been found that 70% of terrestrial precipitation from 26 of the world’s largest river basins comes from evaporation over land through atmospheric moisture recycling (Tuinenburg et al., 2020). On average, a drop of water that evaporates into the atmosphere from the ocean rains out 2.6 times over land before returning to the ocean via river flow (van Noordwijk & Ellison, 2019). An increase in vegetation enhances the interception on rainfall. This water can easily re-evaporate. Theeuwen et al. (2024) shows that the re-evaporation of intercepted precipitation positively correlates with local moisture recycling. Van der Ent et al. (2014) show that re-evaporation of intercepted water, compared to transpiration, typically travels shorter distances through the atmosphere before it returns as precipitation to land.

Land degradation may thus have more profound consequences in the decrease in terrestrial rainfall than has been previously understood (Savenije, 1995). Studies of regreening arid or semi-arid areas show that the albedo and roughness mechanisms are dominated by the moisture recycling feedback mechanism on seasonal and interannual time scales (Yu et al., 2017). The clear link between terrestrial evaporation and terrestrial rainfall strikes the compelling conclusion that terrestrial precipitation is a modifiable quantity through land cover change - for better or for worse.

C. *Afforestation to enhance terrestrial precipitation*

In the context of afforestation, increased plant water availability through enhanced precipitation is crucial for the sustainability of regreening efforts (Huang et al., 2022; Teuling et al., 2019; Wang et al., 2021) and critical to justify investments and design a credible resource management structure. Several recent studies have explored the changes in the atmospheric water cycle following the large-scale afforestation of the Loess Plateau in China completed in 1999 – results show enhanced evapotranspiration (Shao et al., 2019; Tian et al., 2022; Zhang et al., 2022) as well as enhanced local precipitation (Shao et al., 2019; Tian et al., 2022; Wang et al., 2021; Zhang et al., 2021, 2022). Although an increase in evaporation could imply a decrease in water yield (precipitation minus evapotranspiration), studies show that the vegetation rather strengthens the local moisture recycling (also known as the precipitation recycling ratio) (Shao et al., 2019; Tian et al., 2022; Wang et al., 2021). Tian et al. (2022) revealed that the increased vegetation cover has led to a 20.25% increase in precipitation as a result of an overall increase in the humidity of the local atmosphere (+8.49%), heightened soil moisture-vegetation-precipitation feedback (the spatial pattern of soil-moisture increase matches that of precipitation), stronger moisture convergence (+28.26%), and more cloud formation (+8.28%) (Tian et al., 2022).

Although previous afforestation efforts have provided great insight on the role of vegetation in governing weather and climate in those circumstances, there are still important knowledge gaps with respect to understanding the local and non-local effects of afforestation and how this links to meso- and synoptic-scale phenomena (Bosveld et al., 2020). Predicting the wider effects of afforestation, and land cover change in general, on the global terrestrial water cycle requires an understanding of the (non-)biological mechanisms of moisture transport, a widely discussed topic amongst scientists today. Although there is general consensus that vegetation cover plays an important role in the global water cycle (Sheil, 2018), the physical principles behind atmospheric motion and moisture transport, including the role of aerosols, the formation of clouds and the (bio)physical drivers of wind have, however, proven to be less trivial (Marotzke et al., 2017). The biotic pump theory, first introduced by Makarieva & Gorshkov (2007) suggests there is an “evaporative force” driving surface winds - induced by changes in atmospheric pressure caused by condensation above forests. The theory contradicts the longstanding “traditional” theory in meteorology: that the differential heating of the atmosphere is the principle driving force of wind (Bunyard, 2014).

The physical principles of the biotic pump theory have been a topic of debate amongst scientists (Bunyard, 2014; Jaramillo et al., 2018; Meesters et al., 2009; Pearce, 2020), and the role of vegetation in generating rainfall still remains poorly understood (Meesters et al., 2009). The inadequacy of knowledge on the water cycle constitutes a major challenge in foreseeing future water availability and distribution in the context of climate change (Marotzke et al., 2017). The uncertainties that exist in the global understanding of the water cycle is a direct threat to our ability to safeguard the physical processes that ensure the functioning of these intricate natural systems and their capacity to maintain fragile equilibria. An important example of a knowledge gap is the geographical origin of inland rainfall and the biophysical circumstances required to ensure the transport of moisture from ocean land inwards. It is, however, becoming increasingly clear that we must not underestimate the value of vegetation cover in this process and in particular that of near-continuous coastal forests (Makarieva et al., 2009; O’Connor et al., 2021; Sheil & Murdiyarso, 2009).

Most studies on the impact of land cover change on the climate rely on climate models, which have become increasingly sophisticated over recent years (Sheil, 2018) and have supported the understanding of large-scale processes such as large-scale mean precipitation and surface temperature patterns (Flato et al., 2013). However, making predictions based on models inherently assumes these models embody the key interactions that determine the outcome of changing conditions. Over years of research it has become clear that small-scale processes play an important role in governing circulation responses, which cannot be explicitly represented in today's climate models (Marotzke et al., 2017). Disentangling the complex web of causal relationships that make up Earth System is challenging. Simpler climate models that simulate only one primary process can help to understand observations and perform sensitivity analyses.

As highlighted by Marotzke et al. (2017) and Wang-Erlandsson et al. (2022) a crucial strategy in achieving breakthroughs in the realm of climate science and Earth system resilience is to adopt an agile, collaborative approach that transcends disciplinary boundaries and promotes open data sharing principles. As such, the free-flow of ideas may reveal important insights and allows for the cross-examination between simulations and observations. Particularly, future research would benefit from interdisciplinary collaboration between experts in the field of land surface processes (e.g. plant physiology, soil physics) and those in the field of atmospheric science (e.g. boundary layer dynamics and cloud physics) (Beamesderfer et al., 2022). Key gaps include ABL height and diurnal/seasonal dynamics, the bi-directional interactions between surface water (soil/plant moisture) and the atmosphere and land-aerosol-atmosphere interactions (including cloud dynamics and convective precipitation) (Beamesderfer et al., 2022).

Additionally, targeted observations through ground-based or space-borne monitoring schemes are critical to characterise the physical mechanisms of small-scale processes and for model improvement. Sheil (2018) also emphasizes the common mismatch between models and observations, but additionally calls attention to the limitations of conducting only small-scale field studies, as these will not adequately represent large-scale atmospheric behaviour. This stresses the need for extensive field experiments supported by advanced monitoring schemes.
Globally, more research on these effects would contribute to the development of afforestation 'best-practices' – which could ensure that both local and global effects of land-cover transitions are favourable and the resultant overall radiative forcing contributes positively to Earth's energy balance.

III. THE SINAI PENINSULA

A. Geography

The Sinai Peninsula is situated in Egypt, with the Mediterranean Sea and Lake Bardawil to the north, the Negev Desert in Israel to the northeast, the Gulf of Aqaba to the southeast, the Red Sea to the south, the Gulf of Suez to the west and the Nile delta to the northwest. The Sinai is roughly triangular shaped with an area of approximately 61,000 km^2. The peninsula is divided into a number of distinct geographic zones, from a dune field and sand sheets in the north to a mountainous landscape towards the south, reaching an elevation of 2,642 m above sea level at the tip of Mount Catherine, Egypt's highest mountain (Baldi et al., 2020). In general, the Sinai has a desert climate - however, there is a strong spatial variability in average temperature and rainfall especially in the north-south direction. The region characterised by a Mediterranean climate in the north (and desert climate towards the south. Maximum summer temperatures in the north and south vary between 28°C to 37°C and 31°C to 42°C, respectively. Winter day-time temperatures are usually between 10°C to 20°C, occasionally dropping below 0°C during night-time (el Afandi et al., 2013).

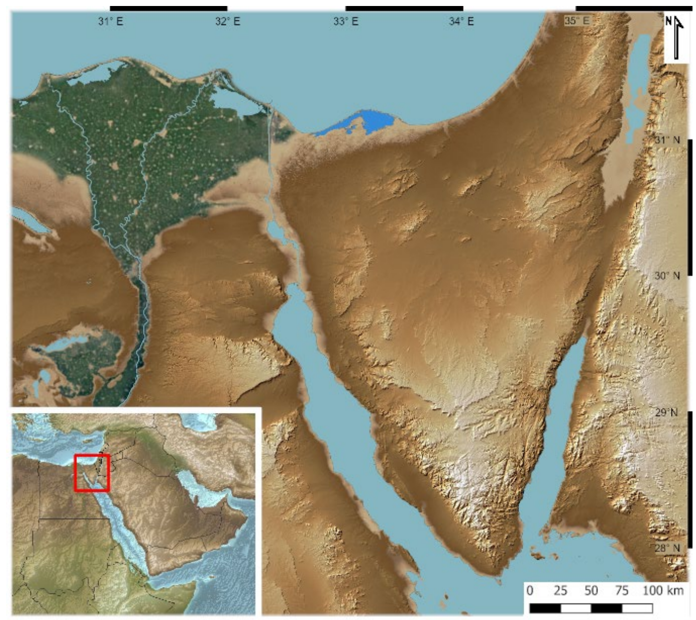

Figure 1. Map showing the Sinai Peninsula and its orography

B. Precipitation patterns in the Sinai Peninsula

On average, 40 mm of precipitation falls in the Sinai Peninsula on a yearly basis with peaks up to 200 mm/yr between the years 2001 and 2020 (Soltani et al., 2023). Precipitation peaks in the northeast of the Sinai Peninsula (Soltani et al., 2023). Precipitation events mainly occur during the wet season between October and March. There is very little precipitation during the dry season (April-September) (Soltani et al., 2023). During the wet season, cyclones mainly contribute to precipitation. Additionally, the Red Sea trough, also a synoptic system, contributes to precipitation in the eastern part of the Mediterranean Basin (Soltani et al., 2023). During the dry season, high-pressure systems that extend from the Atlantic and north of Africa prevent the air from rising and therefore, prevent condensation and limit precipitation (Soltani et al., 2023).

We are not aware of any literature that focuses on the role of the land surface in harvesting rainfall over the Sinai Peninsula. The precipitation events that are studied are mostly linked to synoptic systems and their connection with the land surface remains unknown.

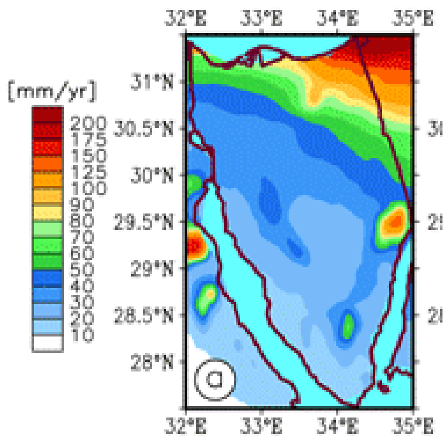

Figure 2: The mean annual precipitation (in mm) in the Sinai Peninsula between the years 2001-2020. This plot is obtained from Soltani et al. (2023).

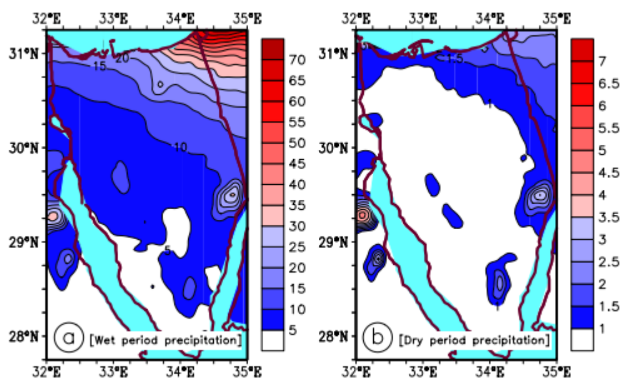

Figure 3: Mean monthly precipitation (in mm/month) in the Sinai Peninsula during (a) the wet season and (b) the dry season for the period of 2001-2020. The wet period ranges from October to March and the dry period ranges from April to September. These plots are obtained from Soltani et al. (2023).

IV. PLANS FOR FURTHER RESEARCH

In addition to the research plans that have been discusses in the previous paragraphs, there are other research opportunities that the natural water production theme would benefit from. To better understand the hydrological effects of the evaporation technology and vegetation it is desirable to quantify their impact on precipitation, not only locally but also non-locally. The large eddy simulation model is the first step into quantifying the impact of the technologies and vegetation on precipitation. However, a more complex model needs to be used to better understand the impact of the evaporation technologies and vegetation on different atmospheric processes. Currently we focus on the processes within the ABL, however, other weather events that result in precipitation and take place on the meso-scale may also be affected by these technologies and vegetation. Such processes and phenomena can be studied using regional or global weather models.

V. BECOME A THEME MEMBER

To become a member of the natural water production research theme and support a PhD project in this theme, a 4-year commitment is needed of 66 kEur/yr. All further costs of the project (lab, materials, supervision, etc.) will be covered by Wetsus, being 3x more. The funding scheme of Wetsus including the contribution of the company member would cover all costs for an entire PhD project.
The company member will be part of the Natural Water Production theme, in which the projects regarding meteorology, solar evaporation and regreening take place. Next to the donor one other company is funding the research. All parties have access to all results of all the projects.

The other theme members have experience in environmental engineering. They aim to design nature-based solutions to restore water cycles and the biosphere. They bring practical expertise to our research collective which helps us to identify and mitigate challenges at an early stage of the development process. In addition, their restoration projects create opportunities for us to test our technological developments in the field. Hence, our partners are crucial to successfully develop the evaporator on a pilot scale.

The researchers in the Natural Water Production theme are supported by different research institutions. We collaborate with experts from Wageningen University from the environmental technology and meteorology departments to develop the evaporation technology and to investigate the involved land-atmosphere interactions. In addition, we collaborate with the plant ecology and nature conservation group to better understand the interaction between vegetation and the environment. Furthermore, researchers from the Copernicus institute at Utrecht University bring expertise on ecohydrology and ecosystem resilience to the research theme.

Company members are part of the wide Wetsus network of companies (>100) and universities (>20). Such a network is well equipped to speed up the development of the technology towards application. Wetsus is also well equipped to generate additional funds to speed up development, at EU, national and local levels.

VI. ACKNOWLEDGMENT

"The Weather Makers Foundation" has been established to set the plan for a regenerated Sinai in motion. This document has been created in a series with several other articles that detail the plan on Regenerating the Sinai. These documents are distributed freely.

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