Expanded Potential Growing Region and Yield Increase for *Agave americana* with Future Climate

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Abstract: Rising crop risk for farmers and greater subsidy costs for governments are both associated with changing climatic conditions, including increased water scarcity. The resilience of *Agave* spp. in both hot and dry conditions, combined with their wide range of uses, position these plants as novel high-yielding crops suitable for both (i) a warming climate and (ii) agricultural regions with finite water resources. A simple model of the physiological response of *Agave americana* to variations in solar radiation, temperature, and precipitation was used to predict *A. americana* yields globally at a 4 km spatial resolution for both contemporary climate and high-end warming scenarios. The potential growing region for *A. americana* expanded by 3–5% (up to 3 million ha) and potential biomass production increased by 4–5% (up to 4 Gt of additional biomass) with climate warming scenarios. There were some declines in biomass with the climate warming projected in smaller dispersed locations of tropical South America, Africa, and Australia. The amount of water required for optimal *A. americana* yield is less than half of the current water required for other crops grown in semi-arid agricultural regions of the southwestern US, and a similar low water demand can be expected in other semi-arid regions of the world. Rock mulching can further reduce the need for irrigation and increase suitable cropland area for *A. americana* by 26–30%. We show that >10 Mg ha^{-1} y^{-1} of *A. americana* biomass could be produced on 27 million ha of cropland without requiring irrigation. Our results suggest that cultivation of *A. americana* can support resilient agriculture in a future with rising temperatures and water scarcity.

Keywords: water use efficiency; agriculture; resilience; crop production; CAM; arid; semi-arid; fiber; biofuel

1. Introduction

Agave americana L., a novel crop species with very high water use efficiency (WUE), can produce dry biomass yields of 9.3 Mg ha^{-1} y^{-1} in semi-arid conditions with less than 600 mm of annual water inputs [1]. With two to four times the WUE of C$_4$ plants [2], crassulacean acid metabolism (CAM) allows these plants to hydraulically isolate (by roots shrinking away from soil contact and stomata closing) during prolonged periods of drought and to photosynthesize at high rates even during periods of extreme heat [3,4]. Stomata open during the night when temperatures are cooler and humidity is higher, which prevents the water loss that would otherwise occur during hot days. This physiological adaptation may serve as an increasingly beneficial trait as temperatures increase and droughts intensify with climate change. Despite the high potential for CAM crops to impart resilience in agroecosystems [5], there is a gap in the current understanding about potential growing locations for novel CAM crops like *A. americana* in dry conditions.

Agave species have been grown and harvested throughout arid, semi-arid, humid subtropical, and tropical regions of the world for food, beverages, fiber, and supplemental animal fodder [5]. Over the last decade, some *Agave* species have been identified for their potential to serve growing bioenergy demands [1,4,6–10]. In addition to drought- and heat-tolerance, CAM is also associated with succulent plants that often have high concentrations of soluble sugars that are easily converted to fuels like bioethanol [4]. While some *Agave* spp. are already commercially cultivated, *A. americana* has cold tolerance that makes it particularly well-suited to conditions at more temperate latitudes [1,5].

Yields from some commodity crops, such as maize that is currently cultivated in both temperate and semi-arid regions, are projected to decline with moderate levels of climate change [11,12]. More frequent drought events in some regions and more frequent flooding in others have led to an increased burden of risk for farmers and higher subsidization costs for governments [13]. Future warming will lead to reduced water availability from snowmelt in semi-arid regions where water is already scarce [14]. CAM plants like *Agave* can provide a more resilient cropping system that may offset the risk of other commodity crops as climate extremes intensify in the future [5]. While some commercial *Agave* crops require irrigation depending on the growing location, there are examples in west central Mexico where *A. mapisaga*, *A. salmiana*, and *A. tequilana* all produced high yields (up to 25–26 Mg ha^{-1} y^{-1}) with no irrigation [15]. In a recent field trial in the southwestern US, *A. americana* was cultivated with as little as 300 mm of annual water inputs [1].

Although *A. americana* is a novel crop, other *Agave* spp. are produced commercially in Central and South America, Africa, and Asia [4–6] and experimental crops are planted in Australia [7,16]. There has been one experimental field trial of *A. americana* in the US [1]. Otherwise, there is no recent history of *Agave* crop production in the US other than in ornamental landscaping, but some recent archeological studies reveal that pre-Colombian populations in the southwestern US cultivated large plantations of *Agave* [17–19].

Archeological evidence indicates that an *Agave* species was cultivated in the southwestern US with both channeled irrigation and rock mulching [17]. Rock mulching is a practice that maintains greater amounts of plant available water by placing a layer of rocks on the soil surface to reduce radiation at the soil surface, thereby decreasing evaporative losses. Evaporative losses from soil are greatest in arid environments, and crops in these locations depend heavily on irrigation. Rock mulching as a soil management strategy has been demonstrated to reduce evaporative losses in arid systems by up to 85% [20], and could potentially negate the need for irrigation of *A. americana* in arid environments.

This study uses an empirical model to predict *Agave* growth in current and future climate conditions. Variable cultivation scenarios were simulated to determine (1) the potential changes in biomass yields with future climate condition, (2) the potential changes in growing region for *A. americana* with climate warming, (3) the reduction in water requirements for *A. americana* relative to current crops in the southwestern US, and (4) if the ancient practice of rock mulching can increase yields while reducing the irrigation needed for optimal production. We simulated yields of *A. americana* globally using the environmental productivity index (EPI) model from [21] and then compared geospatial biomass projections with current climate conditions, future climate conditions with global temperatures 4 °C above pre-industrial levels, optimal irrigation inputs, and rock mulching.

2. Materials and Methods

2.1. EPI Model

A simple model of the physiological response of *A. americana* to variations in solar radiation, temperature, and precipitation was recently developed [21] based on the EPI that was first described as a predictive modeling tool for CAM plants by Park Nobel [22,23]. The model depends on experimentally determined growth responses of a CAM species to light, minimum temperature, and water inputs. The growth responses to each of these environmental factors is fit to a polynomial equation that estimates an index value. The

product of the three indices is an EPI that can be used to predict biomass growth with variable environmental conditions [21–23].

Potential crop biomass from *A. americana* was predicted for each grid cell using the EPI model developed by Niechayev et al. [21]. Environmental parameters (light, temperature, and water) were calculated on a monthly time-step over five years (the anticipated harvest cycle for *Agave*). The light index (α) was calculated as:

$$\alpha = \begin{cases} 0, & for \ I \leq 0.6252 \\ -7 \times 10^{-7}I^2 + 0.0016 \ I - 0.001, & for \ I > 0.6252 \end{cases} \tag{1}$$

where I is the average daily photosynthetically active radiation (PAR) for the month in µmol m^{-2} s^{-1}, and the minimum index limit is 0. The water index (β) was calculated as:

$$\beta = \begin{cases} 0, & for \ P \leq 10.219 \\ 0.0279 \ P - 0.2851, & for \ 10.219 < P < 46.061 \\ 1, & for \ P \geq 46.061 \end{cases} \tag{2}$$

where P is the total monthly input from precipitation in mm, and limits are set for a minimum index of 0 and a maximum index of 1. The temperature index (Γ) was calculated as:

$$\Gamma = \begin{cases} 0, & for \ T \langle -3 \ or \rangle 36 \\ -2 \times 10^{-7}T^5 + 0.13 \times 10^{-4}T^4 - 1.66 \times 10^{-4}T^3 - 3.878 \times 10^{-3}T^2 + 0.1052T + 0.352, & for \ -3 < T < 36 \end{cases} \tag{3}$$

where T is the mean daily minimum nighttime temperature for a given month in °C. We define potentially suitable growing regions for *A. americana* based on a cold hardiness threshold of ≤ -10 °C as described in Section 2.2 below. Temperature maximums are not limiting because *A. americana* has no reduction in carbon assimilation until leaf temperatures reach 50 °C and the plants acclimate to temperatures up to 65 °C [24].

The monthly EPI was calculated as the product of the three environmental indices,

$$EPI_{month} = \alpha \times \beta \times \Gamma \tag{4}$$

then the annual EPI, calculated as the sum of the monthly EPI values, was multiplied by five to simulate growth over a five-year period as:

$$EPI = 5 \times \sum_{0}^{12} EPI_{month} \tag{5}$$

The resulting EPI for the crop was then fit to the linear regression model resolved by Niechayev et al. [21] to calculate total crop dry biomass (Mg ha^{-1}) in each grid cell as

$$Biomass_{crop} = 1.7607(EPI) - 14.774 \tag{6}$$

2.2. Climate Simulations

TerraClimate provides monthly climate and hydroclimate summaries for the land surface of Earth on a 4 km grid during the period from 1958 to the present using data from WorldClim, CRU Ts4.0 and JRA55 [25]. Future climate data from [14] were used to represent high-end warming scenarios where global mean temperatures reach 4 °C above pre-industrial levels derived from an ensemble of 23 global climate model projections from models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) [26]. These data use TerraClimate and a pattern scaling approach from multiple CMIP5 climate models allowing for interoperability with the historical TerraClimate data. The recent climatologies (1981–2010) were used to calculate environmental indices and the EPI for each point on the grid to predict potential yield of *A. americana* geospatially without irrigation. We similarly use a 30 yr climatology compatible with the contemporary data to calculate future EPI without irrigation.

In addition, we calculated irrigation requirements to achieve maximum biomass for both contemporary and high-end warming climates. Optimal irrigation inputs were estimated by calculating the difference between the monthly precipitation and 46 mm, the amount of monthly water input required for the water index Γ (Equation (2)) to reach a value of 1. Secondly, we estimate the effect of rock mulching on the water index for regions where mean annual precipitation (MAP) is less than the optimum (i.e., <46 mm monthly). The additional moisture available for plant growth was estimated by multiplying the monthly water index by 0.83 based on Diaz et al. [20] to account for the reduction in evaporation, i.e., additional soil water retained for plant uptake, due to rock mulching. A new water index value was calculated as:

$$\beta_{rock} = \beta + 0.83\beta \tag{7}$$

Six different scenarios were simulated to estimate and compare biomass yield of *A. americana*:

1. Current (1981–2010) climate;
2. Climate with 4 °C global warming;
3. Current climate with optimal irrigation inputs;
4. Climate with 4 °C global warming and optimal irrigation inputs;
5. Current climate with rock mulch added (simulated only where rainfed MAP was less than optimum); and
6. Climate with 4 °C global warming and rock mulch added (simulated only where rainfed MAP was less than optimum).

In all scenarios, potential growing regions for *A. americana* were constrained to geographical locations where the mean annual absolute minimum temperature (TN_n) is above −10 °C (Supplemental Figure S1), consistent with cold hardiness previously described for this species [27]. Temperatures below this threshold would damage the plants and prohibit viability of the crop. While some studies have resolved contemporary and future cold hardiness zones [28] at spatial scales relevant for agricultural decision-making over the US, such information across global lands is not widely available. We developed a proxy for the mean TN_n by computing the difference between the TN_n and the mean daily minimum temperatures of the coldest month of the year during 1981–2010 from the 0.25 degree ERA-5 reanalysis product. This difference field was then bilinearly interpolated to the mean daily minimum temperature of the coldest month from TerraClimate to derive a global proxy for TN_n (described in more detail in Supplemental Information, Supplemental Figures S2 and S3).

2.3. Analysis of Potential Water Requirements in the Southwestern US

Irrigation requirements for cropland in the southwestern states of Arizona, California, and Nevada were compared to the potential irrigation requirements for *A. americana*. Average annual precipitation (Historical Climatography Series; National Centers for Environmental Information) and irrigation inputs were divided by the total cropland area in each state [29]. Optimal irrigation requirements for *A. americana* were based on the model results described above.

3. Results

Geospatial projections of *A. americana* growth across the globe indicated that precipitation imposed the most widespread constraint on productivity in regions that remain above the minimum temperature threshold of −10 °C (Supplemental Figure S4). Light limitations overlapped with the regions where absolute minimum temperatures were below −10 °C, and temperature limitations within the remaining potential growing regions were less severe than water limitations. Thus, biomass production across the remaining potential growing regions was primarily influenced by water availability, with projected biomass ranging from 0 to 16 Mg ha^{-1}y^{-1}.

Potential biomass production of *A. americana* exceeds 3 Mg ha^{-1} y^{-1} on 53 million ha of land (Table 1), and the greatest crop yields can be expected in South America, subtropical islands and coastlands surrounding the Gulf of Mexico, and the old-world tropical regions of Africa and Southeast Asia (Figure 1a). With optimal irrigation added, the high-yielding growing regions (with yields > 10 Mg ha^{-1} y^{-1}) increase in area from 27 to 73 million ha (Table 1), and include greater portions of Mexico, the Southern US, Northern Africa, India, China, and Australia (Figure 1b). With rock mulching, more moderate yield increases were projected in arid and semi-arid locations due to a greater retention of soil moisture in these locations (Figure 1c).
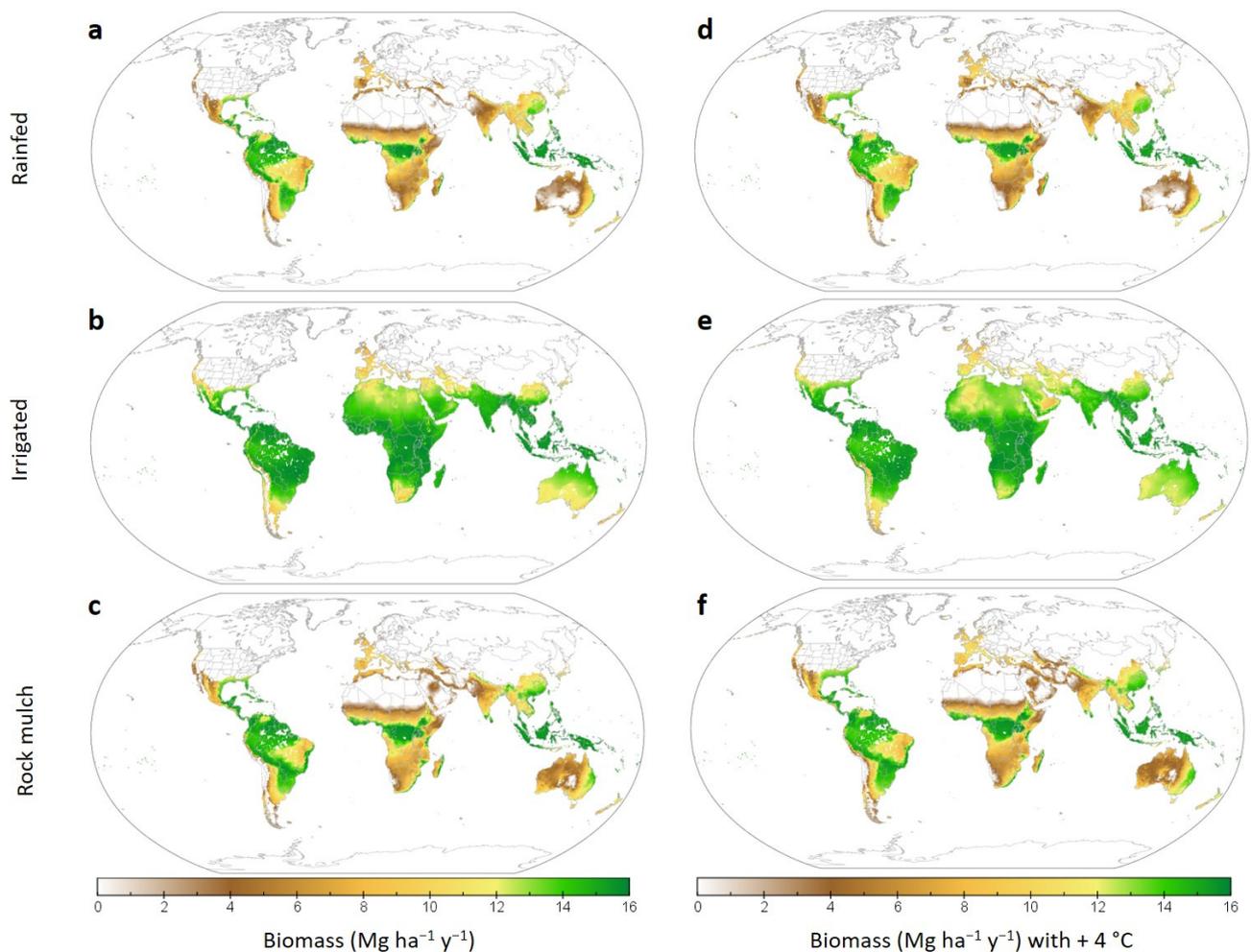

Figure 1. Spatially resolved projections of mean annual biomass production (Mg ha^{-1} y^{-1}) of *Agave americana* over 5 years, simulated with current climate conditions (**left, a–c**) and with +4 °C warming (**right, d–f**) and in conditions with native rainfall inputs only (**a,d**), with irrigation applied to eliminate water limitation to growth (**b,e**), and with rock mulching and no irrigation (**c,f**). The rock mulch management was only simulated in locations with annual water input less than the optimum in panels c and f, but all potential land and biomass are shown on the map (inclusive of both lands without rock mulch and lands with the rock mulch that have water inputs lower that optimum) for comparison with the other simulations. Protected areas and urban areas were also removed from the area of simulation.

Table 1. Summary of potential area (10^6 ha) and potential biomass (10^9 Mg) of *Agave americana* with different scenarios for climate and management.

Climate Scenario	Management	Potential Growing Area (Million ha)			Potential Biomass (Gt)		
		All Land	>3 Mg/ha/y	>10 Mg/ha/y	All Land	>3 Mg/ha/y	>10 Mg/ha/y
1980–2010	rainfed	61	53	27	55	54	36
+4 °C	rainfed	63	55	27	57	55	36
1980–2010	irrigated	76	77	73	107	107	105
+4 °C	irrigated	79	80	77	111	111	109
1980–2010	rock mulch *	66	60	34	65	64	46
+4 °C	rock mulch *	69	63	35	68	67	48

* The rock mulch management was only simulated in locations with annual water input less than the optimum, but numbers in the table are the sum of all potential land and biomass (inclusive of both non-arid lands without rock mulch and arid lands with the rock mulch) for comparison with the other simulations.

The climatically suitable growing region for *A. americana* is predicted to expand in climate warming scenarios by 2–4 million ha (Table 1; Figure 2a,c). Biomass yields increase with future climate change in most regions (Figure 1, right panels), with a total increase of 1–4 Gt depending on management (Table 1). Some decreases in biomass yields were projected in Brazil, Venezuela, Angola, Morocco, Algeria, Tunisia, and Australia due to increased temperatures combined with precipitation changes (Figure 2a). In the scenarios with irrigation applied, there were declines in projected future yields relative to current conditions in Mauritania, Mali, Algeria, Saudi Arabia, Yemen, and Oman. The largest climate-related increases in biomass production, in scenarios both with and without irrigation, were predicted at the margins of the current growing regions. Northerly expansion of the potential crop range was predicted with a warmer future (Figure 2a,c); this is evident in the United States (Figure 2b,d), Europe, and Asia where growth is currently limited by the extreme minimum temperatures. There were also biomass increases predicted in the Southern hemisphere, specifically in New Zealand and the Andes mountain range in South America (Figure 2a,c).
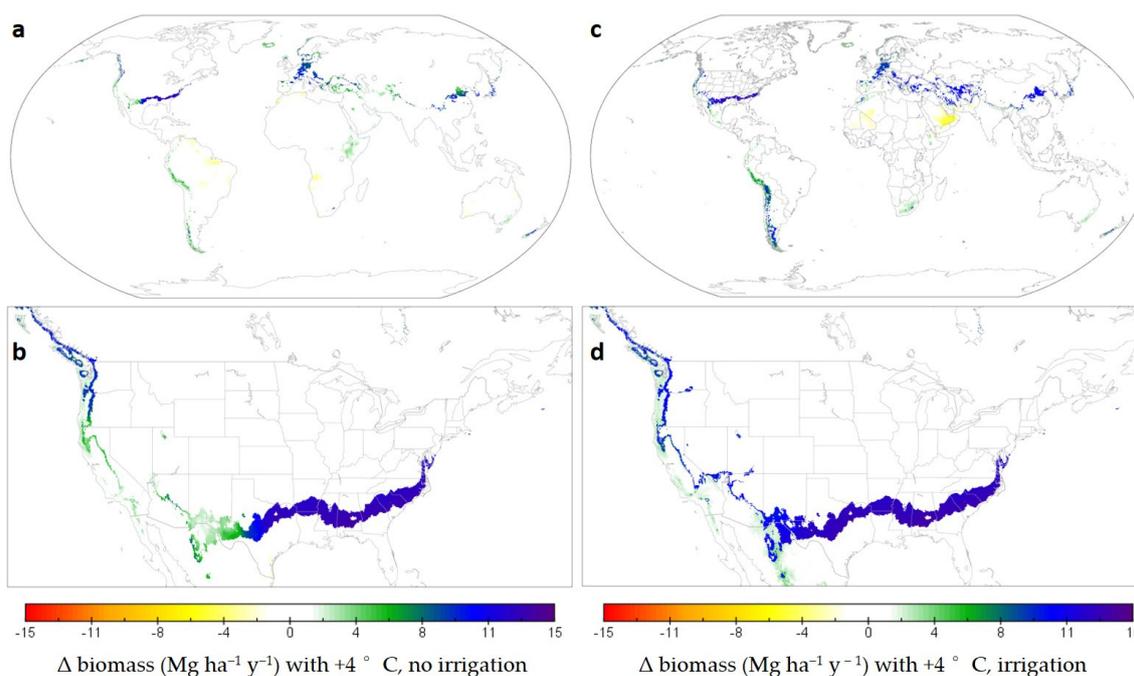
Figure 2. Projected change in potential biomass production (Mg ha^{-1} y^{-1}) of *Agave americana* with + 4 °C warming, globally (**a,c**) and in North America (**b,d**), and simulated with (**a,b**) and without (**c,d**) irrigation.

In North America, *A. americana* yield differences from east to west are due mostly to water inputs. Biomass projections for *A. americana* indicate that the highest yields can be expected in the southeastern US, Caribbean islands, and the Yucatan peninsula (Figure 3) where annual rainfall amounts are high. With irrigation added (Figure 4), total potential biomass yields from *A. americana* increased by 93–96%, and biomass yields can reach optimum amounts even in the arid southwestern US and western Mexico. Rock mulching can also support increased biomass yields of *A. americana* in the dry regions of the southwestern US and western Mexico with less irrigation inputs (Figure 4).
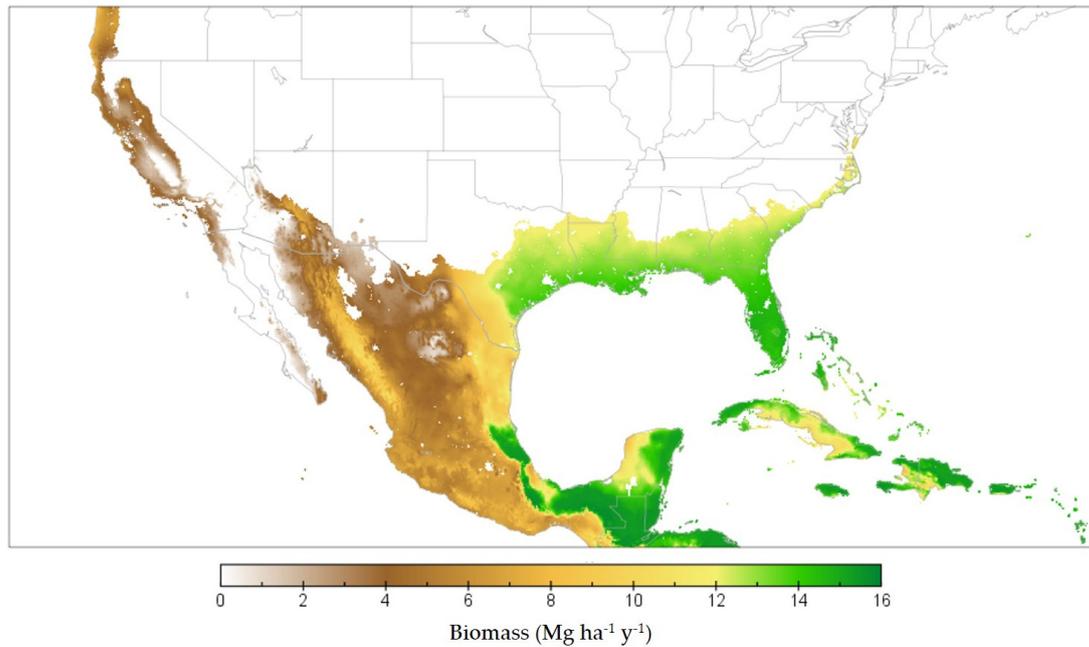

Figure 3. Projections of potential biomass yield (Mg ha^{-1} y^{-1}) for *Agave americana* in North America with current climate conditions and no irrigation.
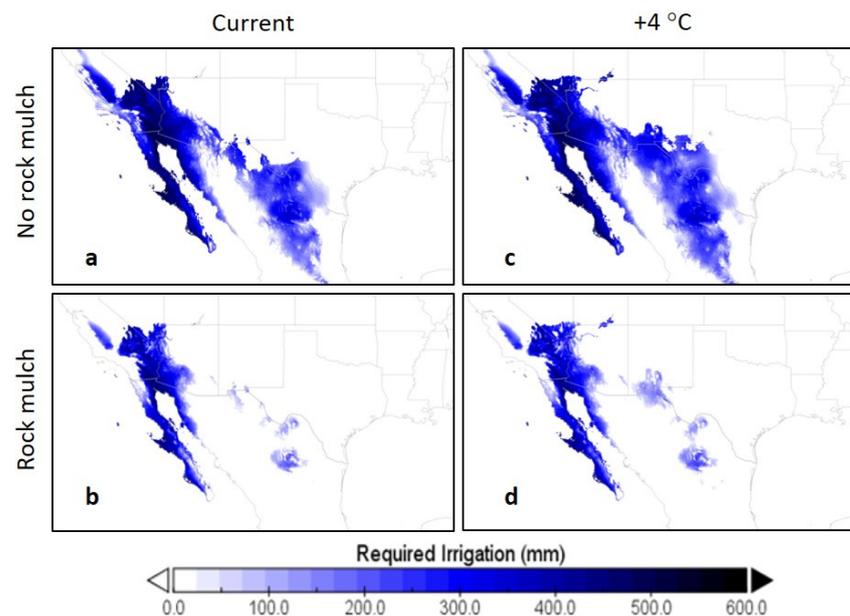

Figure 4. Irrigation required to achieve maximum production of *Agave americana* in the arid southwestern US and western Mexico with recent climate (**a**), with +4 °C warming (**c**), with recent climate plus rock mulching (**b**), and with +4 °C warming plus rock mulching (**d**).

The optimal irrigation amounts for maximizing biomass of *A. americana* are relatively low compared to the current irrigation amounts that are typical in southwestern states of the US. Arizona, California, and Nevada rank highest among all states in the US for the volume of irrigation applied per unit area of cropland, with mean water inputs equivalent to 1344 mm y^{-1}, 948 mm y^{-1}, and 845 mm y^{-1}, respectively [29]. Optimal water inputs (mm) for achieving maximum biomass of *A. americana* (up to 16 Mg ha^{-1} y^{-1}) are 67%, 63%, and 49% lower than the mean water inputs in Arizona, California, and Nevada, respectively, in 2013 (Figure 5) [29].
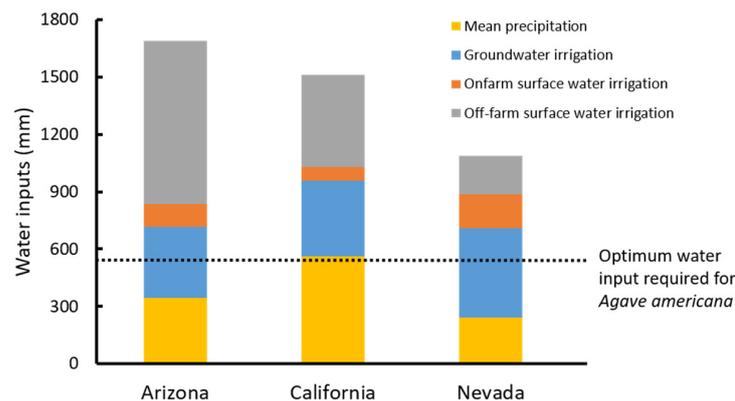

Figure 5. Water inputs from agricultural crops in three southwestern states. Mean precipitation (yellow) reflects the 30-year average [30]. Irrigation from groundwater (blue), onfarm surface water (orange), and off-farm surface water (gray) are distinguished (source: [29]). The dotted line indicates the water requirement required for water to be non-limiting for the growth of *Agave americana*.

4. Discussion

Even though the greatest potential yields were predicted for tropical regions, there are perhaps greater benefits associated with growing *A. americana* in drier regions. Maximum yields will likely not be achieved in arid and semi-arid climates, but *A. americana* can produce greater biomass than many other commodity crops currently grown in these locations and it requires a much lower water input than current crops (e.g., Figure 5). As warming occurs with future climate change, *A. americana* will have an expanded potential growing range, especially at the northern boundaries of the current range for this species. With a future climate that includes +4 °C warming, greater biomass increases would be expected in the northern hemisphere, mostly as a result of increases in minimum temperatures. Only a fraction of the irrigation applied to current crops in arid systems would be required to achieve optimal biomass yields of *A. americana*, making it a more resilient crop alternative for regions like the southwestern US.

Plants that use CAM have underappreciated potential for offsetting risk in agriculture production [5]. Irrigated agricultural lands are estimated to represent half of the economic value of crops which are produced on 28% of national agricultural land in the US [29]. Here, we determined that optimal water inputs of *A. americana* were lower than current irrigation amounts used for common crops in three states that are drought prone. Areas with increasing incidents of extreme drought are a growing liability [31], and *A. americana* provides an alternative crop that can persist through drought conditions [1]. For example, in the San Joaquin valley of California, water trading systems are debated and groundwater depletion as a result of irrigation may require cropland to be fallowed [32]. Investment in new drought resilient cropping systems is warranted [13] and might lower the costs of both irrigation and crop insurance risk in the future. If incorporated into a mixed agricultural landscape, a crop like *A. americana* might reduce the risk of irrigation failure for other crops with higher water demands.

Prior studies indicate that yields will decline for major commodity crops like maize with continued climate change [11,12]. While substantial investment in engineering new

varieties will offset the yield decline with increasingly stressful climatic conditions, there is also tremendous potential, often overlooked, for novel crops like *A. americana* to become resilient alternatives to supplement current crops. In other previous work, we demonstrated the advantage of *A. americana* for biofuel relative to C_4 crops like maize that currently dominates the market [4] and advanced biofuel crops like sorghum and perennial grasses [33]. *Agave americana* also has potential as a resilient fiber crop in arid to semi-arid regions like Arizona, where greater than a ten-fold improvement in WUE (17.5 kg ha^{-1} mm^{-1}) was observed in a field trial [1] relative to the WUE of cotton (1.4 kg ha^{-1} mm^{-1}). There are also potentially other uses for this crop because closely related species have been used for medicinal purposes and sweeteners (see review in [5]).

There is still much to learn about best management strategies for *A. americana* and the yield estimates we report here are likely conservative because they do not account for crop improvement that would be accomplished after farmers gain experience with the new crop. Further gains would come if modern breeding and engineering methods were applied to *Agave* spp. [34]. Recent archeological evidence of large *Agave* plantations in the southwestern US [18] suggest that there is an historical precedent for this type of crop, even if much of the management knowledge has been lost with time. Ironically, resilient agricultural strategies in the future may benefit from mimicking traditional practices of the past.

5. Conclusions

Agave americana is a resilient crop that can offset anticipated agricultural losses from commodity crops due to future climate change. Water inputs required for *A. americana* are less than half those of typical irrigation in arid and semi-arid agricultural regions. The adoption of the cultivation of *Agave americana* may complement other solutions to curtail unsustainable water use in working agricultural lands undergoing aridification with climate change. Likewise, this species has potential as a crop in places that are currently deemed unsuitable for agriculture. Potential yields of *A. americana* are projected to increase in most growing regions as climate change progresses.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11112109/s1, Supplemental Information, Figure S1: Absolute minimum air temperature (°C) mapped on 4 km grid. Contour lines correspond to 10 °C increments, with −10 °C delineating locations where absolute minimum temperatures would kill *Agave americana*, Figure S2: Annual average difference of the average minimum temperature of the coldest month of the year and absolute annual daily minimum temperatures for the period 1981–2020 calculated from ERA-5, Figure S3: Comparison of 1981–2010 average T_{nn} from (a) GHCN stations and (b) TerraClimate. The median absolute error of TerraClimate was 1.0 °C across the 806 stations examined, Figure S4: Indices resolved on a 0–1 scale and mapped on a 4 km grid that constrain the growth of *Agave americana* due to incoming photosynthetically active radiation (a, light index), precipitation (b, water index), and temperature (c, temperature index).

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Data Availability Statement: Outputs, including yield predictions and irrigation maps along with analysis code are available on GitHub at https://github.com/az-digitalag/agave-prediction and archived onon the University of Arizona Research Data Repository (doi:10.25422/azu.data.16828279). Climate data used as inputs to this analysis are from TerraClimate (Abatzoglou et al., 2018, accessed on 1 April 2021). Maps of protected lands are from and the public repositories listed below: UNEP-WCMC and IUCN (2021); Protected Planet: The World Database on Protected Areas (WDPA) and

World Database on Other Effective Area-based Conservation Measures (WD-OECM) [Online], 1 April 2021, Cambridge, UK: UNEP-WCMC and IUCN, available at: www.protectedplanet.net; maps of urban areas from Andy South (2017), rnaturalearth: World Map Data from Natural Earth, R package version 0.1.0, https://CRAN.R-project.org/package=rnaturalearth (accessed on 1 April 2021); Kelso, Nathaniel Vaughn, and Tom Patterson, "Introducing natural earth data-naturalearthdata.com." Geographia Technica 5.82-89 (2010): 25.

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