The Potential for Agrivoltaics in Alameda County

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ABSTRACT

Agrivoltaics are the synergistic combination of photovoltaic panels and agricultural activities on the same unit of land. These systems provide benefits to the food-water-energy nexus through the creation of microclimates that can increase the renewable energy and agricultural output of a given unit of land. Agrivoltaic systems have the potential to increase land use efficiency and reduce the conflict between the land intensive agricultural and renewable energy industries. Alameda County's land resources, climate, and agricultural industry present great potential for the implementation of agrivoltaics. In order to evaluate the potential for agrivoltaics in Alameda County, I conducted a Land Suitability Analysis using ArcMap to find parcels with favorable social, environmental, and physical factors for agrivoltaic systems. The Land Suitability Analysis revealed that areas in Northern Livermore have the most potential for agrivoltaics that can increase land use efficiency. I then gathered climatic data from the National Solar Radiation Database (NSRDB) and input it into the Simulateur mulTIdisciplinaire pour les Cultures Standard (STICS) and System Advisory Model (SAM) models to estimate the crop and solar energy output under agrivoltaic and separate production scenarios for three different agricultural activities: viticulture, ranching, and shade crops. Agrivoltaic systems produced 1747.59 kWh/kw while separate production generated 1729.07 kWh/kw in all three systems. Viticulture yields were 883 fruits/m^2 in agrivoltaics and 1202 fruits/m^2 in a control scenario. Shade crop yield remained unchanged between agrivoltaic and separate production scenarios. I compared the expected energy and agricultural production of modeled agrivoltaic and separate production systems using the Land Equivalence Ratio to produce a metric of land efficiency. The Land Equivalence Ratios for viticulture, ranching, and shade crops were 1.74, 1.01, and 2.01 respectively. Understanding that agrivoltaics can increase the land efficiency of parcels in Alameda County while providing renewable energy to densely populated urban areas and unlocking underutilized agricultural lands provides incentives for public and private industries to further study and potentially implement these systems.

KEYWORDS

land equivalence ratio, land suitability analysis, rangevoltaics, photovoltaics, land efficiency

INTRODUCTION

Anthropogenic climate change is heightening the need for renewable energy systems that supply growing energy needs without jeopardizing critical habitat zones and agricultural land. California produced 277,704 gigawatt-hours (GWh) in 2019, 57% of which came from renewable energy sources (California Energy Commission 2019). Renewable energy capacity requires a drastic increase in order to meet the state's ambitious climate goal, outlined in Senate Bill 100, of producing 100% of electric retail sales to end-use customers from renewable or zero-carbon resources by 2045 (California Energy Commission 2019). However, large scale solar energy production methods place large demands on land resources, creating conflict with conservation and agricultural needs (Dinesh and Pearce 2016). With President Joe Biden and California Governor Gavin Newsome implementing legislation to protect and preserve wildlife habitats, Senate Resolution 372 and Executive Order N-82-20 respectively, increasing efficiency of finite land resources takes on a new importance (Office of Governor Gavin Newsome 2020). The need for renewable energy coupled with the increased protection of critical habitat zones creates a unique problem that large scale renewable energy production methods alone cannot solve alone (Dupraz et al. 2011).

Agrivoltaics are a potential solution to mitigate land conflicts, satisfying both the renewable energy needs and spatial limitations of peri-urban, or urban adjacent, environments while offering agricultural benefits. Agrivoltaics are the placement of photovoltaic panels over crops at a height which allows farm machinery to operate and the crops to receive some amount of sunlight. The placement of solar panels above agriculturally productive land serves to increase land efficiency, renewable energy production, and crop yields (Barron-Gafford et al. 2019). Studies have shown that agrivoltaics have potential to benefit both livestock and crops by creating microenvironments under solar panels, reducing heat stress, and reducing the rate of evapotranspiration (Sharpe et al. 2021). However, agrivoltaic systems are not widely utilized because they are a relatively new and developing technology that require more extensive research. Additionally, agrivoltaics cannot be applied in all agricultural settings, as some environments may not have suitable physical conditions to support the production of both renewable energy and crops.

One area with potentially favorable environmental conditions for the implementation of agrivoltaics is Alameda County, California. Alameda County has a semi-arid climate with relatively little available water, making it a candidate for the placement of agrivoltaic systems. The reduced rates of evapotranspiration, cooler temperatures, and protection from heat stress that agrivoltaics offer could increase the agricultural productivity of the region (Barron-Gafford et al. 2019). Agrivoltaics may be especially useful to Alameda County's agriculture industry as large amounts of agriculturally zoned land have seen little to no development since the passing of Measure D in 2002, which set an urban growth boundary to protect agricultural lands (Bazar 2019b). The implementation of agrivoltaic systems on existing rangelands could take advantage of renewable energy production with little to no effect on livestock (Sharpe et al. 2021). Agrivoltaics may present Alameda County with an opportunity to generate renewable energy without jeopardizing agricultural land, as well as diversify and even increase crop yields.

My research will explore the potential for agrivoltaics in Alameda County. First, I will determine where the most viable locations for agrivoltaics are in Alameda County. Then, after selecting areas suitable for agrivoltaics, I will determine if agrivoltaic systems increase land efficiency compared to separate production. Separate production is defined as photovoltaic arrays and crop fields that are spatially separated, as opposed to agrivoltaics which put photovoltaic arrays over crops. I will evaluate land efficiency based on how agrivoltaic systems affect crop yield and renewable solar energy production compared to the production of separated agricultural and photovoltaic farms. Findings from this study will provide information about an emerging technology and a method of evaluation for local, state, and federal governments looking to implement and incentivize sustainable development of renewable energy resources without jeopardizing agricultural activity.

BACKGROUND

Unincorporated Alameda County

The Bay Area has a Mediterranean climate characterized by warm, dry summers and mild, wet winters (García-Herrera and Barriopedro 2018). Alameda County contains more specific microclimates with cooler temperatures in western regions closer to the bay and warmer temperatures and higher seasonal variation in the East past the foothills along the Hayward Fault.

The annual temperature ranges from a minimum of -2.78°C to a maximum of 41.1°C with an average of 15.7°C. The average amount of precipitation annually is 52.8 cm with virtually no rain in the summer months and much of the rainfall occurring in the winter and early spring (Koppen Climate Classification n.d.). There are typically higher temperatures and lower water availability in the Northeastern regions of the county, which is where a majority of the county's agricultural zoned land is located.

Alameda is second to San Francisco in population density of Bay Area counties with approximately 2,000 persons per square mile according to 2010 Census data (U.S. Census Bureau n.d.). Alameda County is highly developed, especially in the Western areas of San Leandro, Oakland, and Fremont as well as Northern areas like Dublin, Pleasanton, and Livermore. The most populated areas are in the western region of the county where Berkeley and Oakland are located (Statistical Atlas n.d.). Urban sprawl, or the rapid expansion of built infrastructure, is prevalent in commuter cities including Dublin and Pleasanton located in the Northern Region of Alameda County (Cozad et al. 2002).

The state of agriculture and renewable energy in Alameda County

Agriculturally productive lands, most commonly vineyards and rangelands, are clustered around the Southern and Eastern boundaries of Livermore. Large swaths of agriculturally zoned lands are present along the urban growth boundary in the Northern regions of the county as well as South of presently active agricultural activities in Livermore. Most of the agriculturally productive lands and potentially productive lands are in unincorporated Alameda County, outlined in orange in Figure 1 (Cozad et al. 2002). Unincorporated Alameda County is separated from cities like Dublin, Pleasanton, and Livermore by the urban growth boundary. The urban growth boundary was set by Measure D, a county policy passed in 2002 which set developmental boundaries in East Alameda County to prevent urban sprawl from large cities from encroaching on potential agricultural lands (Bazar 2019b). Most of the land protected by Measure D is open, undeveloped perennial grassland with scattered, low intensity agriculture such as hay production. Alameda County’s most productive agricultural activities are viticulture, followed by livestock production and a combination of orchard and shade crops (Bazar 2019a).

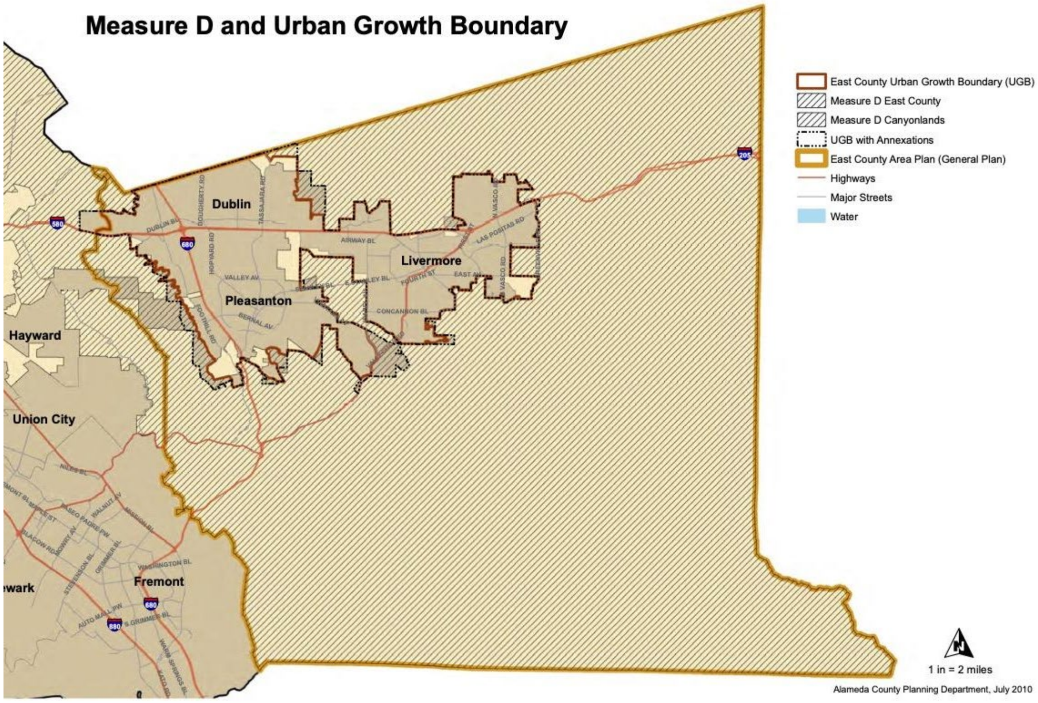


Figure 1: Measure D Boundary. This map shows the limit of the urban growth boundary in red surroundings of major cities bordering Alameda County's unincorporated lands.

With the recent approval of the Aramis agrivoltaic project, Alameda County is ripe with opportunity for agrivoltaic development in its largest industries. A semi-arid climate and lack of water availability, along with the recent approval of an agrivoltaic project suggests agrivoltaics could be the key to unlocking agricultural productivity in regions protected by Measure D.

Agrivoltaics: definitions and suitable systems

Agrivoltaics are the placement of photovoltaic panels over agriculturally productive farmland. The synergistic combination decreases heat stress on crops and livestock, subsequently increasing crop yield while trapping water vapor released by crops during evapotranspiration, thus creating cooler microenvironments beneath solar panels and increasing their efficiency. Reduced rates of evapotranspiration, due to a decrease in temperature beneath panels from a reduction in solar radiation reaching the ground and vegetation, also serve to limit water inputs for farmers (Barron-Gafford et al. 2019).

Photovoltaic array formation is one of the most important factors of agrivoltaic system. Meaningful characteristics include panel density, height, tracking, which can be tailored to specific industries to allow more sunlight, allow the use of machinery, or prevent livestock from interfering with renewable energy production. Panel height and row separation can be changed to allow for specific machinery or agricultural activities to take place below. Additionally, panel angle and tracking method, the selection of fixed, single axis tracking, or dual axis tracking, can be modified based on a systems primary function whether it's to maximize solar production, crop production, or optimize land efficiency. The angle and aspect of the panels themselves can also be altered to change the amount of solar irradiance reaching the ground, the amount of solar energy produced, and soil moisture (Barron-Gafford et al. 2019).

METHODS

Study site description

Alameda County is a densely populated urban environment with a varied Mediterranean climate and substantial agricultural activity and potential, especially in the Eastern regions of the county. Alameda County is highly developed, especially in the Northwestern areas of San Leandro and Northern areas like Dublin, Pleasanton, and Livermore. There are typically higher temperatures and lower water availability in the Northeastern regions of the county, which is where a majority of the county's agricultural zoned land is located (García-Herrera and Barriopedro 2018).

Although the entirety of Alameda County was mapped and analyzed, the focus of this study lies on unincorporated lands. Unincorporated lands are outside of city limits, protected by Measure D, and typically more agriculturally productive than lands within city limits. Measure D is a county policy passed in 2002 which set an urban growth boundary in East Alameda County to prevent urban sprawl from cities like Dublin and Livermore from encroaching on potential agricultural lands. Most of the land protected by Measure D is open, undeveloped perennial grassland with scattered low intensity agriculture like hay production. Agriculturally productive lands, especially vineyards and rangelands, are clustered around the Southern and Eastern boundaries of Livermore (Cozad et al. 2002).

Geospatial mapping and land suitability analysis

The first step in determining viable locations for agrivoltaic systems was locating and importing relevant geospatial datasets with social and environmental factors that will influence the geospatial model. I conferred with local agricultural and solar experts to determine the types of data layers required. Then, I used national, regional, state, and county open data portals to locate quality geospatial data sources, which were then downloaded and imported into ArcGIS Version 10.8.1 (ESRI 2020). A table of the geospatial data layers and their sources is included in Appendix A.

After importing each shapefile into ArcGIS, I ensured each layer was defined in the World Geodetic System 1984 Universal Transverse Mercator Zone 10N projection and was properly downloaded. Performing these actions yielded a comprehensive map of Alameda County with environmental and social data, which enabled the execution of a land suitability assessment.

After creating a comprehensive geospatial map, I performed a Land Suitability Analysis using ArcGIS to create opportunity and constraint layers which combined to reveal the most opportune areas for agrivoltaic development.

I began my land suitability analysis by ensuring each layer of interest was clipped to display information within the boundary of Alameda County. I then separated layers based on their influence on agrivoltaics as an opportunity or constraint. I defined three potential scenarios relating to the implementation of agrivoltaics in Alameda County. Scenario 1 is an aggressive implementation scenario where agrivoltaics are implemented on all available lands excluding conservation areas. Scenario 2 is a moderate scenario where agrivoltaics are only implemented on productive and potentially productive agricultural land. In this scenario, conservation lands and private lands are defined as constraints. Scenario 3 is a conservative implementation scenario where agrivoltaics are only implemented on potentially productive agricultural lands. In Scenario 3, USDA Prime Farmland, conservation areas, and private lands are defined as constraints.

Table 1. Land Suitability Analysis Classifications and Function. A "+" signifies that the layer was weighted with the value "+1" in its respective scenario. A "-" signifies that layer was weighted with the value "-1" in its respective scenario. An "x" denotes a layer with weight 0, which eliminates that area from contention.

Layer	Scenario 1	Scenario 2	Scenario 3	Applied Function
Agricultural Parcel Zoning	+	+	+	Select agricultural zones, weight 1
Transmission Lines	+	+	+	Build 609.6 m buffer around, weight 1
Slope	+	+	+	Select slopes $< 7.2^{O}$, weight 1
Aspect	+	+	+	Select SW, S, SE aspects, weight 1
USDA Prime Farmland	+	+	-	Select prime farmland, weight 1
Private Lands	+	-	-	Select private lands, weight 1
Conservation Lands	x	x	x	Select conservation lands, weight 0

I created a buffer of 609.6 m around the Transmission Lines layer as agrivoltaics are most opportune on parcels within 609.6 m of a transmission line with the potential for grid connection (Massachusetts Department of Energy Resources 2018). Additionally, I selected for slopes less than 7.2° as those areas are prime for agricultural and grazing activity (Jarasiunas 2016). Opportunities and constraints layers are shown in Table 1 along with the associated ArcGIS function that I applied.

After I assigned functions and weights for all opportunity and constraint layers, I used the Raster Calculator tool to add the cell values of all the individual geospatial layers and output a new raster. I analyzed the map and assigned a color gradient to the final suitability composite value, which revealed areas of high suitability in dark purple colors contrasted with areas of low suitability in light green. I made land recommendations based on composite values.

Modeling for land equivalence

For the purposes of this study, I modeled three different agrivoltaic systems tailored to three of Alameda's most productive or potentially productive agricultural industries. I will model agrivoltaic systems for viticulture and ranching, which are Alameda County's two most productive agricultural activities, as well as a system geared towards shade-tolerant row crops, which make up a small portion of the County's agricultural activity but have potential for expansion when paired with agrivoltaics (Bazar 2019a).

I used environmental data from high potential areas discovered in the Land Suitability Analysis to model solar and crop output for three different industries, which I then used to estimate land efficiency using the Land Equivalence Ratio. I used climatic data from the National Solar Radiation Database (NSRDB) to collect inputs for solar and crop models, which informed land equivalence.

After locating viable lands in the Land Suitability Analysis, I took climatic Typical Meteorological Year (TMY) data from the NSRDB and used them as inputs in the System Advisor Model (SAM) from the National Renewable Energy Lab (NREL) to model solar production. TMY data was also used in the Simulateur mulTIdisciplinaire pour les Cultures Standard (STICS, or multidisciplinary simulator for standard crops) crop model to estimate yield for the viticulture and shade crop scenarios described later (Brisson et al. 1998).

System advisory model

According to the NSRDB, the Direct Normal Irradiance (DNI) within Alameda County ranges between 5.5 and 7.5, but the range within the areas that have the highest potential for agrivoltaics according to the Land Suitability Analysis generally falls between 6.5 and 7. For this reason, I chose climatic data from a TMY from an area with high potential that presents a DNI of 6.85 (Sengupta et al. 2018).

Table 2: Inputs and Outputs of the SAM Model. The System Advisory Model requires the inputs listed below. I obtained these inputs using the National Solar Radiation Database from the National Renewable Energy Laboratory to obtain Typical Meteorological Year (TMY) data for Alameda County.

Inputs	Units	Outputs	Units
Direct Normal	kWh/m2/day	Total Electrical Output	kWh/m2/day
Diffuse Horizontal	kWh/m2/day		
Average Temperature	° Celsius		
Average Wind Speed	meter/second		

Latitude/Longitude	Decimal Degrees
Elevation	meter
Time Zone	N/A
Time Step	Minutes

Modeled systems had a nameplate capacity of 1 kWdc, using standard modular type, on a fixed axis, with a panel tilt of 30°. A nameplate capacity of 1 kWdc normalized the results from the SAM model and, because the model is linear, allowed them to be applied to variable parcel sizes; this allows for scaling system sizes based on the parcel size. Using the Parametrics function in the PVWatts model along with TMY climatic data from Alameda County in the year 2020, it was projected that a panel tilt of 30° would maximize the energy yield of both the agrivoltaic and separate production systems (Sengupta et al. 2018).

While the agrivoltaic systems will have varying characterisitcs depending on the type of agricultural activity they're built for, the solar models conducted in this study will apply for all three agricultural activities modeled. The most impactful variables in the model for these scenarios were panel tilt and tracking system type, and these remain unchanged between the systems suited for viticulture, ranching, and shade crops. I used the SAM model to estimate electrical output for an agrivoltaic system and separate production system which applied to all three agricultural activities. Table 3 contains the model characteristics for each agrivoltaic system.

Table 3: Model Characteristics. The table displays the characteristics or agrivoltaic systems suited for different agricultural activities. In the SAM model, system tracking, panel type, and panel tilt are the only variables that make significant changes to the total electrical output.

Characteristics	**Viticulture**	**Ranching**	**Shade Crops**
System Tracking	Fixed	Fixed	Fixed
Panel Type	Standard	Standard	Standard
Panel Tilt	30°	30°	30°

Panel Height (m)	1	3	4
Inter-Panel Spacing (m)	2.5	N/A	1

In practice, agrivoltaic systems will vary in panel height and panel spacing depending on the agricultural activity the system is suited for, but minor variations caused by these variables are outside of the scope of this study. To simulate solar production in an agrivoltaic system, air temperature in the TMY file used by the SAM model will be reduced by 1.5 °C to simulate cooling caused by the trapping of evapotranspiration from crops beneath the panels. The temperature reduction in ambient air will reduce panel operating temperature, subsequently increasing panel efficiency. Barron-Gafford et al. 2019 found that the reduction of incoming energy under agrivoltaic systems yielded cooler daytime air temperatures, averaging 1.2 + 0.3 °C lower compared to separate production (Barron-Gafford et al. 2019). This exact temperature reduction is not well established, but Barron-Gafford's result is a verified finding and a good estimate.

Viticulture. The model system outline for viticulture utilized repeating gaps of 2.5 meters that exist between trellises. Although grapes are normally considered a full sun plant, it is still possible to grow grapes in mostly shade with preparation and forethought to maximize yield. Solar panels are placed so that the middle of each panel is at the same height as the top of the trellis. According to Malu et al., panels are fixed at 1 meter, which is about half the distance between the trellises so the shade from the array will not fall on the grape crop for most of the year. Panel tilt, height, and placement varied based on the location and trellis arrangement on the farm (Malu et al. 2017). In Alameda County, a panel tilt of 30° maximized energy yield.

Ranching. Model systems for ranching are less technically restrictive because of the lack of agricultural inputs and expected outputs. With a focus on livestock production, solar array placement can prioritize renewable energy production while still offering shade to reduce the heat stress on livestock. According to Sharpe et al., in an experimental scenario, panels were mounted 2.4 to 3 meters from the ground so cows could not reach the panels. In these scenarios, single axis or dual axis tracking may offer more benefits as these systems maximize solar energy production. For the purposes of this study, fixed arrays were modeled. Panels can be placed at a higher density compared to agrivoltaic systems with a focus on crops because the amount of solar radiation reaching the ground is not a limiting factor in the production of livestock (Sharpe et al. 2021).

Shade crops. To model a system with a focus on shade crops, I used techniques from peer reviewed works by Majumdar and Pasqualetti, and Barron-Gafford et al. to achieve accurate estimates. Panels were placed at a height of 4 meters where the panel's lowest point rested at 3.3 meters above the surface whereas they were only about 0.3 - 1.0 meters above the ground in the traditional PV configuration (Majumdar and Pasqualetti 2018). There was 1 meter of spacing between each row of PV panels and panels were placed at half density (Barron-Gafford et al. 2019). Fixed axis systems with a panel tilt of 30° were modeled in this study. There is the possibility to manually modify the tilt angle of the solar panels in the range or employ single or dual axis tracking systems to allow more radiation to reach the crops at some sensitive phenological stages. Adaptive reconfiguration schemes to reduce the effect of shadows on solar panels by modifying the tilting angle have been proposed to increase the power output of the solar PV array but vary based on individual system and location (Dupraz et al. 2011).

Simulateur mulTIdisciplinaire pour les cultures standard

The STICS crop model was used to obtain crop yield data for crops as the model uses generic parameters, which are applicable to most crops. The STICS model consists of four main modules that pertain to the growth of the plant, interaction of the soil with the plants, the crop management module dealing with the farming techniques applied to the crops and the micro climate model which enumerates the effects of climate and soil water content on the climate surrounding the immediate vicinity of the crops. For the purposes of this study, only climatic data and plant type were altered (Dinesh and Pearce 2016).

The same TMY climatic data from the NSRDB used earlier in the solar modeling portion was used for the inputs of the STICS crop model. Some data was altered. Maximum and minimum temperature values were calculated using data from the TMY file in order to match the inputs that STICS required. Additionally, Global Horizontal Irradiance (GHI) values were converted from watts to joules and normalized on a scale from 0 to 40 in order to fit within the bounds of the STICS model. Atmospheric carbon dioxide was an additional input not contained in the TMY file.

The carbon dioxide input was 417 ppm according to NASA's atmospheric carbon dioxide concentration data ("Carbon dioxide concentration | NASA global climate change" n.d.).

I selected Syrah as the model grape variety and lettuce as the model shade crop as they are supported in the STICS crop model and are grown in Alameda County. First, I created outputs for aerial biomass at harvest for the lettuce and number of harvested fruits for grapes using the original TMY file. These estimated yield values served as the agricultural output estimates under separate production scenarios. I then modified the climatic data, decreasing the minimum and maximum temperature values by 1.5 ºC (Barron-Gafford et al. 2019). I also modified the values of global irradiance, decreasing the values by 26% for the agrivoltaic system for viticulture and 30% for the agrivoltaic system for shade crops to simulate the shading caused by solar panels (Malu et al. 2017) (Elamri et al. 2018).

Land equivalence ratio

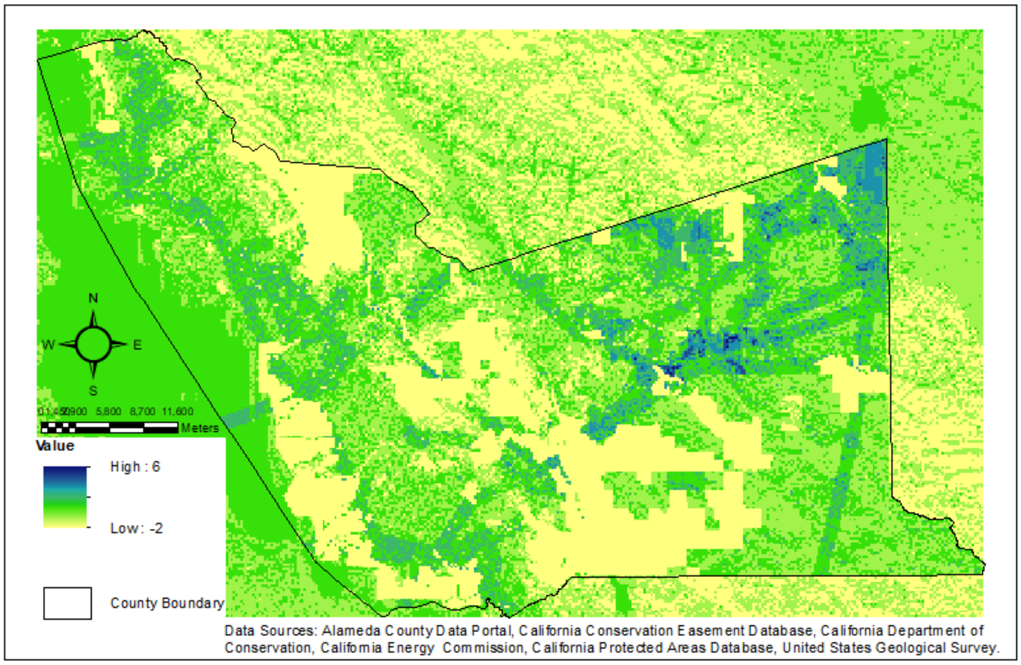
I then took the outputs for agrivoltaic and separate system production and entered them into the land equivalence ratio for each of the three systems. The land equivalence ratio is $LER = (Y_{Crop}\text{ in AV} / Y_{Monocrop}) + (Y_{Electricity}\text{ AV} / Y_{Electricity}\text{ PV})$. I compared model outputs for each agrivoltaic system against a common control of separate production, which will yield an efficiency ratio (Trommsdorff et al. 2021).

I expected that crop models would predict yields ± 8% of their control size (Dinesh and Pearce 2016). With the assumption that panels are mounted on a fixed tilt, I expect a 1% increase in annual electric yield in agrivoltaic systems compared to separate production (Barron-Gafford et al. 2019). I expect that agrivoltaics models will yield land equivalence ratios near 1.4, meaning that the productivity of an agrivoltaics system on 100 km^2 of land yields the production of separate production on 140 km^2 of land (Dupraz et al. 2011).

RESULTS

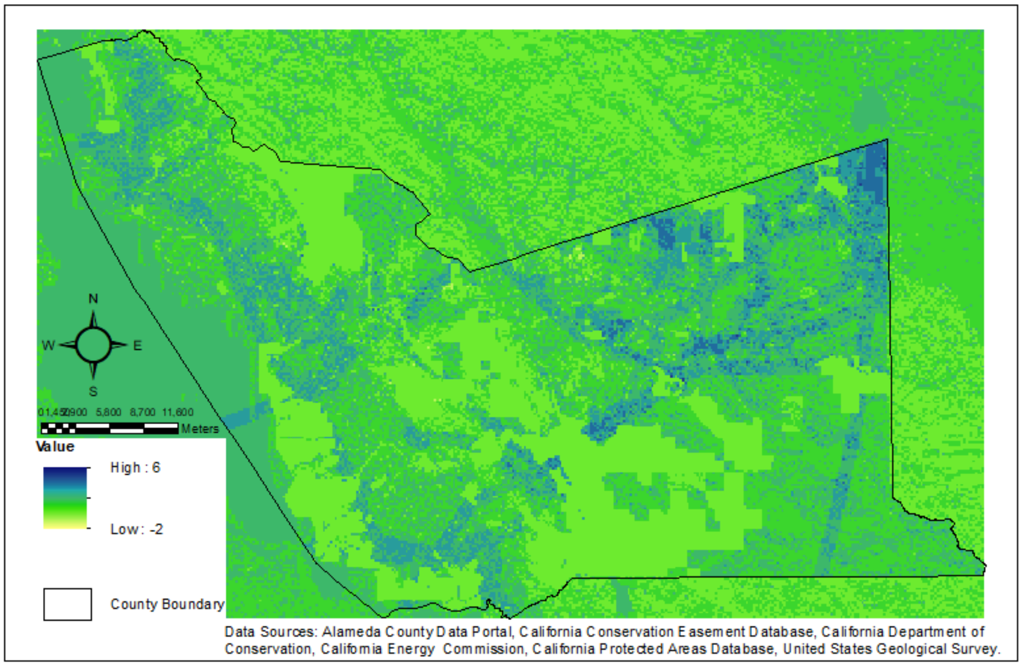
Land suitability analysis

After conducting the land suitability analysis scenarios, I found that the area of Northeastern Livermore had the highest composite opportunity score for all three estimated scenarios. Northeastern Livermore had the highest composite land suitability analysis score due to the areas' extensive transmission network, the presence of USDA Prime Farmland, the lack of conservation protected land, gradual slope, and Southern facing aspect. Areas in central Livermore, South of highway 580 received high composite land suitability analysis scores. Scores were not as high as Northeastern Livermore because of the lack of USDA Prime Farmland in the area.



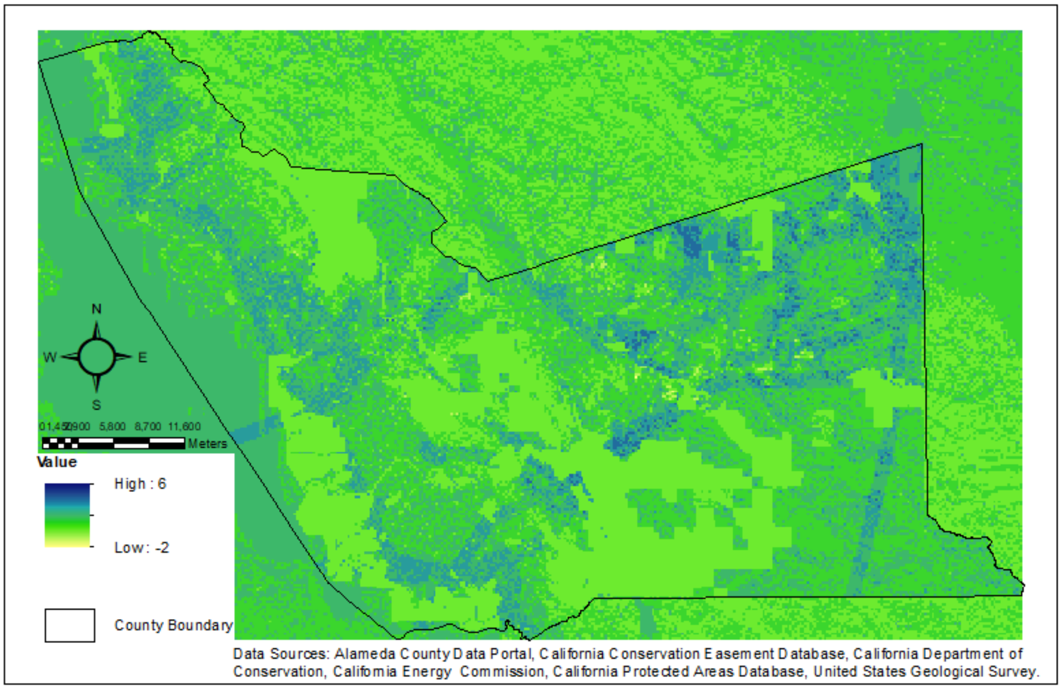
Data Sources: Alameda County Data Portal, California Conservation Easement Database, California Department of Conservation, California Energy Commission, California Protected Areas Database, United States Geological Survey.

Figure 2: Land Suitability Analysis Scenario 1. The figure below shows the final land suitability analysis for scenario 1. Scenario 1 represents an aggressive agrivoltaic implementation scenario where systems are considered on public lands as well as prime agricultural land. Areas of high potential are displayed in a dark purple color.



Data Sources: Alameda County Data Portal, California Conservation Easement Database, California Department of Conservation, California Energy Commission, California Protected Areas Database, United States Geological Survey.

Figure 3: Land Suitability Analysis Scenario 2. The figure below shows the final land suitability analysis for scenario 2. Scenario 2 represents a moderate agrivoltaic implementation scenario where systems are considered on prime agricultural land, but not public land. Areas of high potential are displayed in a dark purple color.



Data Sources: Alameda County Data Portal, California Conservation Easement Database, California Department of Conservation, California Energy Commission, California Protected Areas Database, United States Geological Survey.

Figure 4: Land Suitability Analysis Scenario 3. The figure below shows the final land suitability analysis for scenario 3. Scenario 3 represents a conservative agrivoltaic implementation scenario where systems are not considered on public or prime agricultural land. Areas of high potential are displayed in a dark purple color.

Modeling for land equivalence and land equivalence ratio

Under the agrivoltaic systems, panels generated 1747.59 kWh/kw, while under a separate production scenario, model outputs for solar generation were 1729.07 kWh/kw. This represents a 0.01% increase in solar production in agrivoltaic systems compared to separate production. For viticulture, agricultural productivity reached 883 fruits/m^2 in agrivoltaics. Under a control scenario, yield reached 1202 fruits/m^2. The Land Equivalence Ratio value for viticulture was 1.74.

Under the rangeland agrivoltaic or rangevoltaic system, studies have shown livestock were not significantly impacted by the installation of photovoltaics over grazing land (Sharpe et al. 2021). The Land Equivalence Ratio value for ranching was 1.01.

For the model agrivoltaic system geared toward shade crops, agricultural productivity reached 0.52 tons/hectare. Under a control scenario, lettuce yield remained at 0.52 tons/hectare. The Land Equivalence Ratio value for shade crops was 2.01.

DISCUSSION

Agrivoltaics have the potential to not only change the interaction between renewable energy and agricultural production but change the standard methods of production for these resources all together. Agrivoltaics serve to increase land efficiency by harnessing the synergistic interactions between photovoltaic arrays and the agricultural activities beneath them. The combination of photovoltaic arrays and agriculture will reduce conflicts between the land intensive renewable energy and agricultural industries as well as increase crop production, improve panel efficiency, reduce water inputs, and increase carbon dioxide uptake in crops (Barron-Gafford et al. 2019). To maximize potential benefits, a Land Suitability Analysis (LSA) was performed to determine where the most viable locations for agrivoltaics resided within Alameda County. The LSA showed that Northeastern Livermore is the area with the highest potential for agrivoltaic systems. Modeling three agricultural scenarios under control and agrivoltaic systems returned expected crop yield and a 0.01% increase in energy yield in agrivoltaics. For viticulture, the estimated crop yield was 883 fruits/m^2 under an agrivoltaic system compared to the estimated crop yield of 1202 fruits/m^2 under separate production. Creating a Land Equivalence Ratio for each of these three agricultural activities yielded estimates of land efficiency. For viticulture, the estimated LER was 1.74. For ranching, the LER was 1.01. For shade crops, the LER 2.01.

Land suitability analysis

The Land Suitability Analysis revealed that areas in East Livermore have the most potential to support agrivoltaic systems. Parcels in this area received the highest composite score in the map of the final suitability analysis because of the number of opportunities present. East Livermore has the most potential for agrivoltaics because of the ease in access to transmission lines, the presence of proper agricultural zoning, gentle slopes, southern facing aspect, lack of conservation, and the existence of USDA Prime Farmland, which all act as opportunities in the development of agrivoltaics.

Another area with relatively high composite suitability scores was Northern Livermore. This area is similar to East Livermore in terms of the density of transmission lines, agriculturally zoned land, favorable slope and aspect, and lack of conservation zones, but this area does not have USDA Prime Farmland.

It is important to understand the layout of the opportunity and constraint factors as they directly enable or inhibit the development of agrivoltaic systems. The presence of transmission lines enables agrivoltaic systems to connect their photovoltaic arrays to the public power grid, which can supply nearby urban environments with demanded renewable energy. Agrivoltaic systems will likely only be developed on land zoned for agricultural use, therefore, agriculturally zoned land is an opportunity for this development. Alternatively, agrivoltaic systems cannot be built on land protected for conservation purposes, so understanding where these barriers to development exist is critical to planning potential projects. Gentle slopes and southern facing aspects are beneficial for any farming operation. Gradual slopes allow for the use of mechanical farming equipment while southern aspects increase the amount of incoming solar irradiance, which is especially important when considering crops will receive reduced amounts under agrivoltaic systems. USDA Prime Farmland is land with the best combination of physical and chemical features able to sustain long term agricultural production (California Department of Conservation n.d.). Agrivoltaic systems can maximize the potential of agricultural lands, therefore, existing productive farmland would make a sensible target for agrivoltaic development.

Knowing where agrivoltaic systems are possible allows the modeling of their expected agricultural and energy outputs as well as project planning. This should be the first step in any attempt at agrivoltaic development. Once the mapping of environment and social factors result in potential areas of agrivoltaic development, physical climatic factors of those potential areas are used to perform crop and solar energy models to understand the expected performance of agrivoltaic systems in these potential areas.

Modeling for land equivalence and land equivalence ratio

To determine the effect agrivoltaics have on land efficiency, the Land Equivalence Ratio was used along with estimated crop and renewable energy outputs generated in the modeling section. A Land Equivalence Value was generated for each of the three agricultural activities listed above: 1.74 for viticulture, 1.01 for ranching, and 2.01 for shade crops.

Agricultural and renewable energy output estimates were created using the STICS crop model and SAM solar model with climate data from the NSRDB. Models suggest that agrivoltaics increase land efficiency by producing more renewable energy compared to separate production without significantly inhibiting agricultural production (Dinesh and Pearce 2016). Agrivoltaic systems increase land efficiency through shading by the PV panels, which provides multiple additive and synergistic benefits including reduced plant drought stress, greater food production and reduced PV panel heat stress (Barron-Gafford et al. 2019). These benefits can be applied to a variety of agricultural activities including viticulture, ranching, and the production of shade-tolerant crops.

Viticulture

Although grapes are a relatively shade-intolerant crop, they are a crop of interest for several reasons. Reasons for potential include the fact that viticulture is Alameda County's most productive agricultural activity, grapes are grown on trellises such that there is an underutilized gap of about 1.5–2.5 m between the trellises allowing for the installation of photovoltaic arrays, it is still possible to grow grapes in mostly shade with some preparation and forethought to maximize yield (Malu et al. 2017). Agrivoltaic systems generated 883 fruits/m^2 and 1747.59 kWh/kw compared to 1202 fruits/m^2 and 1729.07 kWh/kw in separate production. The Land Equivalence Ratio returned values of 1.74 for viticulture.

Ranching

According to previous studies, agrivoltaic systems incorporated into ranching activities may reduce the intensity of heats stress in livestock and increase well-being of livestock and the efficiency of land use (Sharpe et al. 2021). Agrivoltaic systems generated 1747.59 kWh/kw compared to 1729.07 kWh/kw in separate production. The Land Equivalence Ratio returned values of 1.01 for ranching.

Shade crops

Shade-tolerant crops are an obvious target for agrivoltaic systems because shade-tolerant crops are the most likely to minimize any negative impacts the shade from photovoltaic arrays has on agricultural production (Dinesh and Pearce 2016). Agrivoltaic systems generated 0.52 tons/hectare and 1747.59 kWh/kw compared to 0.52 tons/hectare and 1729.07 kWh/kw in separate production. The Land Equivalence Ratio returned values of 2.01 for shade crops.

The Land Equivalence Ratios for agrivoltaics systems are high in previous studies, suggesting that it may be very efficient to produce electricity and to harvest food crops on the same land unit (Amaducci et al. 2018). A ratio of 1.74 means an agrivoltaic system of 100 km will produce as much as 174 km of separate production of agricultural and renewable energy activities.

Agrivoltaics would produce more renewable energy and more food while using less water, fortifying the security of all three of these critical natural resources (Proctor et al. 2021). Agrivoltaics would help meet growing urban demand for renewable energy and reduce conflict between the renewable energy industry, agricultural industry, and environmental activists through the preservation of agricultural and conservation land. The deployment of agrivoltaic systems would also help provide a growth boundary to this sprawling urban area by helping preserve agricultural land, encourage greater population density, reduction in commuting emissions, and promoting local farming (Majumdar and Pasqualetti 2018). Agrivoltaics also have the potential to expand the range and yields of certain crops. Additionally, agrivoltaics reduce agricultural water inputs and increase the efficiency of photovoltaic panels by creating cooler microclimates beneath panels (Barron-Gafford et al. 2019). Past studies found that 20% of the US' total electricity generation can be met with Agrivoltaic systems if less than 1% of the annual US budget is invested into agrivoltaic infrastructure (Proctor et al. 2021). Agrivoltaics serves as a promising new tool in the future to sustainable agriculture and renewable energy production.

Limitations

One of the main limitations of this study is the fact that it is a case study on the potential for agrivoltaics in Alameda County, therefore, the results cannot be generalized to other countries or regions. This study can, however, serve as a template for conducting similar studies on the potential for agrivoltaics in different regions. The same methods and techniques can be applied to gain an understanding of the objective, physical and social factors influencing the potential development of agrivoltaic systems as well as model their expected output and estimate land efficiency.

Within the context of this study, there are several limitations from a geospatial modeling perspective. Some of the more obvious limitations come from geospatial data layers that were not included in the land suitability analysis but do have real implications in the development of agrivoltaic systems. Geospatial layers for solar irradiance, soil types, and water availability were not included in this study. Soil types do affect the ability to grow crops in agrivoltaic systems, however, consideration of soil characteristics was out of the scope of this project. I assumed that developers that had the resources to implement agrivoltaic systems would also have the resources to acquire water and irrigate land. Mapping the complex network of above and below ground water availability was an additional factor outside of the scope of this study. There are basic assumptions present in every land suitability analysis that present limitations. For example, most opportunities and constraints were weighted with a "+1" or "-1" respectively. These are very basic values that do not convey the true significance a geospatial factor can have on the potential to develop an agrivoltaic system.

Additionally, geospatial mapping and production modeling do not consider social and economic aspects tied to the development of agrivoltaics. There are several additional factors to consider when planning agrivoltaic projects including a farmer's willingness to implement the system, public perception of the project, and a cost-benefit analysis that considers the cost of the system versus the expected returns in yield and renewable energy output.

Future directions

This study presents a framework for discovering the potential for agrivoltaics in other countries and regions. In addition to using this methodology to explore areas of potential development, studies can also focus on studying different crop types and how they react under agrivoltaic systems. Additionally, further research is needed regarding the actual effects agrivoltaic systems have on crop yields. Crop models should be verified by agricultural experiments looking at yields of different crops under the climatic conditions presented by agrivoltaic systems.

To determine the full potential of agrivoltaic development in Alameda County and other areas of interest, more research is needed with regards to the social and economic aspects of agrivoltaics. Stakeholder meetings employing analytical hierarchies should be conducted to properly weigh geospatial opportunities and constraints. Public meetings are necessary as well to gauge social perceptions of agrivoltaics and how they might affect potential legislation regarding the development of these systems. Cost-benefit analyses should be conducted on potential agrivoltaic systems to ensure there is economic incentive for farmers and solar developers have a reason to build.

Broader implications

Agrivoltaics have the potential to increase land efficiency, reduce agricultural inputs, and improve environmental conditions for crop and renewable energy production. Agrivoltaic systems significantly reduce air temperatures, direct sunlight, and atmospheric demand for water compared to separate production. With some crops, agrivoltaic systems can increase carbon dioxide uptake, total yield production, and water use efficiency. Soil moisture increased under agrivoltaic systems and water vapor from plant transpiration create cooler temperatures beneath solar panels subsequently increasing panel efficiency (Barron-Gafford et al. 2019).

Agrivoltaics can produce renewable energy without jeopardizing or creating conflict with agricultural activities. These systems change the conventional thought that land use is a zero-sum-game of competition between renewable energy and agricultural food production. Additionally, locating agrivoltaic systems in urban or peri-urban environments can provide large scale renewable energy production close to areas of high demand (Barron-Gafford et al. 2019).

Agrivoltaic systems can increase the land efficiency of agricultural land in Alameda County. Based on environmental, climatic, and social factors, agrivoltaics are objectively possible. These systems can be sustained by the opportune environmental factors present in the Northern and Eastern areas of Livermore. This work is a case study and exact results cannot be generalized to other regions; however, promising results can provide a hopeful outlook as well as incentive for further research in areas with similar climatic conditions.

The methods and structure of this study can be broadly applied to other geographic areas. Performing a land suitability analysis using geospatial data from any location can provide an insight into the potential for agrivoltaics in that area. Taking climatic data from favorable locations found in the land suitability analysis enables crop yield and solar energy modeling, which will provide insight into the effect agrivoltaics have on land efficiency.

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APPENDIX A: Land Suitability Analysis

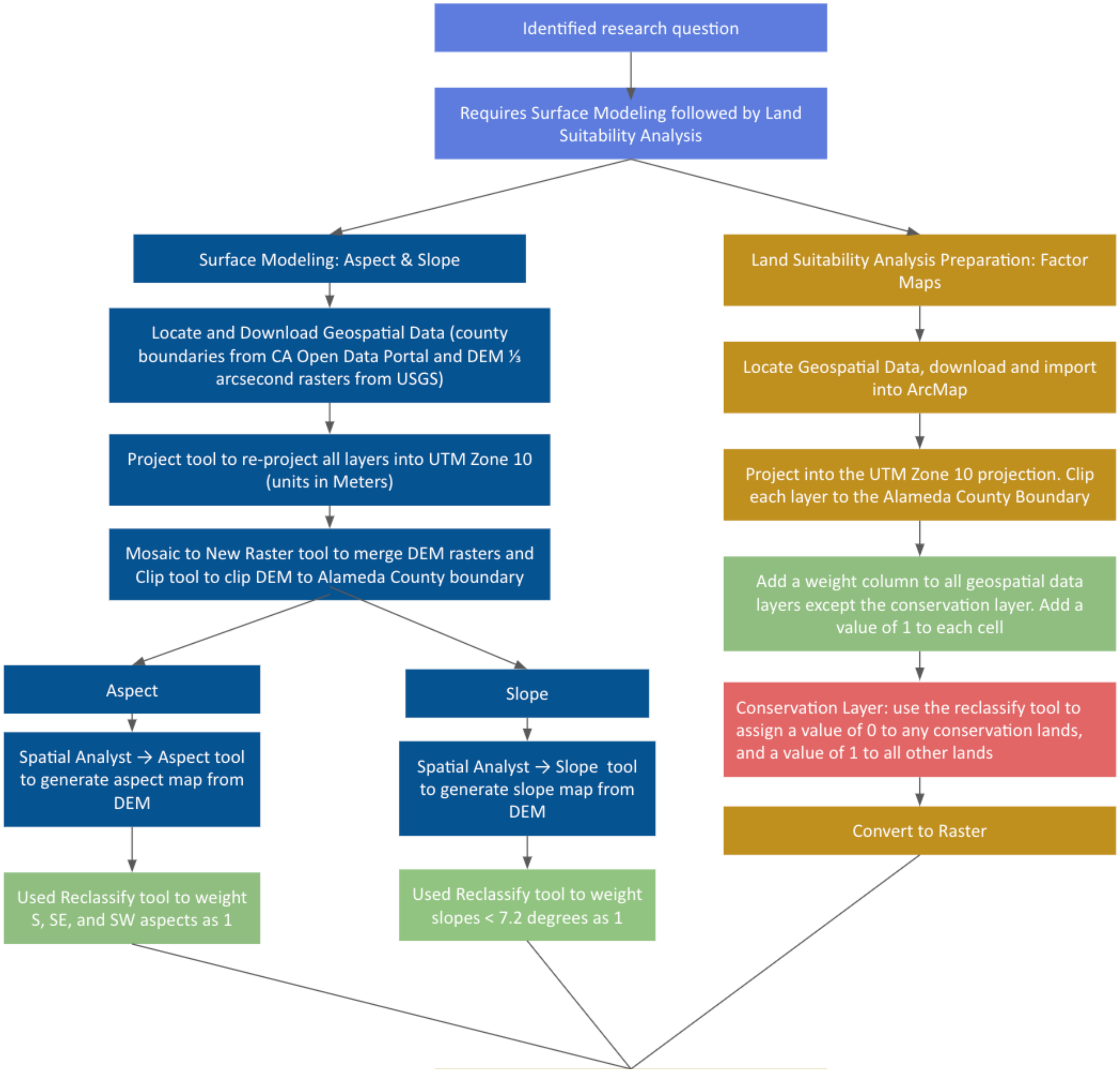

Figure A1: Land Suitability Analysis Flowchart. This figure shows the flow of logic as well as the ArcGIS functions used to execute each step in the Land Suitability Analysis.

I used the Map Algebra Raster Calculator in order to create the final suitability analysis map by combining the individual raster layers. For each scenario, I would create a composite raster containing the summation of the opportunities and constraints, then I would multiply that new raster by the conservation lands raster in order to exclude protected lands from the final suitability raster. Below is a table that associates the common name of the geospatial with the name of the raster as it exists in ArcMap.

Table A1: Layer Name Common and Raster Calculator: This table acts as a reference linking the names of layers in the raster calculator to their common name referenced throughout the paper.

Layer Common Name	Layer Name in Raster Calculator
Aspect	Reclas_aspf
Slope	Reclass_slop2
Transmission Lines	Transline_ras
Private Lands	Easeland_ras
Agriculturally Zoned Land	Agzoning_ras
USDA Prime Farmland	Primeland_ras
Conservation Lands	reclass_cons0

The code used to calculate composite raster layers using the Map Algebra tool in Raster Calculator is listed below. Each scenario contains two calculations. The first step is to sum all the opportunities and constraints while converting null values to have the numeric value “0”. Once all factors are added, the second step is to multiply the composite layer and the conservation layer so that any areas that overlap with conservation lands are given the value “0”.

- Scenario 1:
    - SCENE1_OPP = (Con(IsNull("Reclas_aspf"), 0, "Reclas_aspf") + Con(IsNull("Reclass_slop2"), 0, "Reclass_slop2") + Con(IsNull("Transline_ras"), 0, "Transline_ras") +Con(IsNull("Easeland_ras"), 0, "Easeland_ras") + Con(IsNull("Agzoning_ras"), 0, "Agzoning_ras")) + Con(IsNull("Primeland_ras"), 0, "Primeland_ras")
    - SCENE1AF = “Scene1_OPP” * “ reclass_cons01”

- Scenario 2:
    - (Con(IsNull("Reclas_aspf"), 0, "Reclas_aspf") + Con(IsNull("Reclass_slop2"), 0, "Reclass_slop2") + Con(IsNull("Transline_ras"), 0, "Transline_ras") + Con(IsNull("Agzoning_ras"), 0, "Agzoning_ras") + Con(IsNull("Primeland_ras"), 0, "Primeland_ras") - Con(IsNull("Easeland_ras"), 0, "Easeland_ras"))
    - SCENE2AF = “SCENE2_OPP” * “recla_cons01”
- Scenario 3:
    - (Con(IsNull("Reclas_aspf"), 0, "Reclas_aspf") + Con(IsNull("Reclass_slop2"), 0, "Reclass_slop2") + Con(IsNull("Transline_ras"), 0, "Transline_ras") + Con(IsNull("Agzoning_ras"), 0,"Agzoning_ras") - Con(IsNull("Primeland_ras"), 0, "Primeland_ras") - Con(IsNull("Easeland_ras"), 0, "Easeland_ras"))
    - SCENE3AF = “SCENE3_OPP” * “recla_cons01”

APPENDIX B: Geospatial Data Sources

Table B1: Layer Data Source: This table provides the data source for every geospatial data layer used in the Land Suitability Analysis.

Layer Common Name	Data Source
Slope & Aspect	U.S. Geological Survey, 20211116, USGS 1/3 Arc Second n38w123 20210617: U.S. Geological Survey. U.S. Geological Survey, 20220206, USGS 1/3 Arc Second n38w122 20220206: U.S. Geological Survey.
Transmission Lines	California Energy Commission, California Electric Transmission Lines, 2021, https://cecgis-caenergy.opendata.arcgis.com/datasets/260b4513acdb4a3a8e4d64e69fc84fee_0
Private Lands	California's Protected Areas, California Conservation Easement Databse, 2021, https://www.calands.org/cced/.
Agriculturally Zoned Land	Alameda County Data Sharing Initiative, Alameda County Parcel Boundaries, 2022, https://data.acgov.org/datasets/b55c25ae04fc47fc9c188dbbfcd51192_0/about.
USDA Prime Farmland	California Department of Conservation, California Important Farmland: 2018, 2022, https://maps-cnra-cadoc.opendata.arcgis.com/datasets/cadoc::california-important-farmland-2018/about
Conservation Lands	California's Protected Areas, California Protected Areas Databse, 2021, https://www.calands.org/cpad/.
Alameda Boundary	California Department of Forestry and Fire Protection, California County Boundaries, 2022, https://gis.data.cnra.ca.gov/datasets/CALFIRE-Forestry::california-county-boundaries/about