SITE SUITABILITY ANALYSIS: SMALL-SCALE FIXED AXIS GROUND MOUNTED PHOTOVOLTAIC POWER PLANTS IN FRESNO, CA

by

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To my mom and dad, Judy and David, my brother Fred, my grandma and grandpa, Pai-Chung Chi and Yue-Feng Wang, and my partner in life, Bonnie for their everlasting support in everything I do. With special thanks to Devon Munsell for his advice and willingness to help. I would also like to thank Dr. Daniel N. Warshawsky for serving as my committee chair and his timely feedback despite his busy schedule. And Last but not least, I would like to thank Dr. Laura C. Loyola and Dr. Katsuhiko (Kirk) Oda for taking time out of their busy schedules to serve on my thesis committee; their comments and timely feedback were much appreciated

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List of Abbreviations

USC	University of Southern California
CA	California
GIS	Geographic information system
GCC	Global Climate Change
PV	Photovoltaic
MW	Megawatt
kW	Kilowatt
DEM	Digital elevation model
USGS	United States Geological Survey
CUP	Conditional Use Permit
CSP	Concentrating solar power
NREL	National Renewable Energy Laboratory
CEC	California Energy Commission
BRE	Building Research Establishment
FLOWA	Fuzzy logic ordered weight averaging
ANN	Artificial neural network
NAD	North American Datum
SQL	Standard Query Language

Abstract

As Global Climate Change (GCC) becomes an increasingly pressing issue, the shift towards renewable energy has renewed urgency. Not only will renewable energy bring us closer to energy independence and energy security, but it will also yield cleaner air and mitigate the severity of the effects of GCC. Solar currently generates roughly 2.7% of the United States' power, leaving much room for improvement. Small-scale photovoltaic farms tend to be cheaper and easier to develop than their larger counterparts. As decentralized energy plays an important role in energy security having many small plants rather than few large plants prompted the inspiration for this thesis.

This thesis incorporates GIS techniques to determine suitable sites for small-scale (1-20 MW) fixed-axis flat panel photovoltaic (PV) solar farms in Fresno County, CA. By employing street, parcel, and zoning data from the Fresno County website, Digital Elevation Model (DEM) data from the United States Geological Survey (USGS), and transmission line data within Esri's ArcGIS 10.2 (and tools such as the Area Solar Radiation and Slope tools), this thesis identifies suitable sites for a small scale fixed axis photovoltaic plant. By visualizing this information, we provide a guide for developers to reference for future developers, government decision makers, and researchers. Ultimately, this thesis was able to take a large sample size of available land, and narrow it down to a few thousand parcels based on suitability in the categories listed above, and illustrate it on a map in a meaningful way. A key observation that resulted from this study was that a lack of human infrastructure and terrain were the primary limiting factor when it comes to site suitability for PV plants, which is also a common observation with many previous studies.

Chapter 1 Introduction

This chapter provides the impetus for this thesis, an overview of renewable energy, solar electricity, PV development on agricultural land, solar radiation modeling, and the technologies used in PV generation.

1.1 Motivation

Today, our world is faced with an ever growing energy demand that needs to be met by our energy supply. Our past and present reliance on fossil fuels has led us to question our ability to continue to grow sustainably. With about 80% of our energy coming from fossil fuels in the 20th century, if our continued reliance on fossil fuels continues in a “business as usual” manner, it will lead to soaring greenhouse gas emissions, a decrease in energy security, air pollution at local and regional levels resulting in health issues, and a lack of universal access to energy (Johansson et al. 2012, xii). In fact, it is estimated that at the present rate of consumption, within 50 years, our petroleum reserves will be depleted (Demirbas 2009, 212).

Energy security and energy independence are also critical reasons why renewable energy sources will continue to become more important in our world. As of 2009, an estimated 63% of our global oil reserves were in the tumultuous Middle East (Demirbas 2009, 212). Given the recent instability in the Middle East, our energy security is more readily brought into question. In fact, using fossil fuels as our main energy source has led to serious energy crises in the past (Demirbas 2009, 219).

As our concern for global warming is continuously being exacerbated by our increased energy consumption, states are now recognizing renewable energy forms as a way to cut down on emissions as well as to build a sustainable community. For example, in 2011, California

Governor Jerry Brown signed legislation that would require California utilities to get one-third of their power from renewable sources by the year 2020 (McGreevy 2011).

As one of the few mainstream renewable energy sources used today, solar power will become increasingly important to sunny California in the coming years. The primary motivation for this thesis is to help identify and visualize suitable sites for utility-scale ground mounted fixed-axis solar PV farm development in Fresno, CA to promote energy independence, reduce our carbon footprint, and fulfill the renewable portfolio mandated by Governor Brown.

This thesis focuses on land with current agricultural uses due to their wide open, flat land characteristics. On top of that, choosing these rural agricultural lands for renewable energy development can create jobs and opportunities in these rural areas, reducing the global trend of migration towards urban areas (Panwar et al. 2011, 1514). Being able to harvest this renewable energy in a decentralized fashion (unlike fossil fuels), will allow us to sustainably and reliably meet rural and small-scale energy demands (Panwar et al. 2011, 1514).

This thesis applied and enhanced previously used methods and models to create a model to find suitable sites for a small-scale fixed-axis flat panel PV solar farm. This model, based on various criteria, may provide data or even serve as a model for future researchers and studies. This model may be useful for researchers and developers to be able to visualize optimal sites for future solar farm development. Ideally, this thesis can help to alleviate the stress on the environment, which originated from our greedy energy consumption habits. Though it is a relatively small scale study area, the methods developed as a part of this this can be used to help identify optimal sites in other regions, and have a meaningful impact at a larger scale. As every little step counts, producing an impact even at a relatively small scale would have meaningful impact in our fight against GCC.

This thesis considers variables including solar radiation, land accessibility, land area, land use, grid proximity, and slope to identify suitable parcels for solar farm development in Fresno, CA. These data were acquired through the USGS, the Fresno County website, as well as a past researcher. Geographic position suggests that more southern counties may be more ideal for solar installations, because they are closer to the equator. However, there may also be northern counties which would be ideal locations for solar PV development due to the direction in which the slope is facing; this thesis serves as a model to identify optimal sites for solar development in these northern counties of California.

In order to understand why Fresno County in particular was selected for this thesis, it is important to outline some of Fresno County's environmental as well as legislative characteristics. Fresno is geographically located relatively in the center of California, in a fairly flat plain area, and is mainly utilized as agricultural land which can be developed into PV generation plants with a Conditional Use Permit (CUP). The large, wide-open flat lots with a sunny, desert climate provide a prime environment for solar PV installations. This prime environment makes for good reason to pursue this thesis.

Identifying suitable sites in Fresno County is important not only for the improvement of the environment, but also to shed light on the amount of untapped clean energy we might have access to. Furthermore, estimating and modeling solar potential can help us visualize the latent energy within our reach, as well as bolster public awareness in bringing renewable energy sources to the grid. In doing so, this thesis aims to use its methodology to serve as a model for future researchers studying the similar topics in their community.

1.2 Renewable Energy Today

As the global energy demand goes up, we must continuously find ways to expand our supply in order to meet this growing demand. As fossil fuels are a limited resource, and will inevitably run out, we must seek out other sources of energy to satiate our growing energy demand. As of 2011, energy from renewable sources (including biomass, hydropower, geothermal, solar, wind, and ocean thermal) supplied 14% of the world's total energy demand (Panwar et al. 2011, 1513). With our global energy consumption growing at about 2% a year (most of it in fossil fuels), renewable resources will continue to play an important role in meeting our energy demands (Johansson et al. 2012, xii).

Aside from nuclear technologies, renewable energy such as solar energy, is very much seen as one of the few potential replacements for fossil fuels, when they do run out. As global supply is still about 80% dominated by fossil fuels, there is much room for the renewable sector to grow. In fact, in the United States, as of 2012, renewables make up only 8% of total energy consumption (Munsell 2011, 2).

Renewable resources used as of 2015 include solar, hydroelectric, wind, biomass, geothermal, and ocean thermal technologies. Though the technologies only make up a relatively small fraction of our energy supply, these technologies have the potential to help us build towards energy independence and sustainability. Biomass resources for example, include energy generation from sources such as agriculture and forest residues, algae, grasses, manure, organic wastes, and other biomaterials (Demirbas 2009, 215). In industrialized regions, biomass resources represent about 3% of the total energy consumption, while in rural places or less developed regions, biomass accounts for up to 90% of the total consumption, especially in the poorest countries (Demirbas 2009, 216).

California does a decent job at using clean energy sources for its electricity production, generating most of its electricity from natural gas. During the year 2010 in the state of California, hydroelectric electricity accounted for 16.4% of the state's net power generation, while other renewables accounted for 12.5%; over 50% of the total energy was generated from natural gas while coal and petroleum together accounted for only 1.5% of net generation (US. Energy Information Administration 2010, 27). Though natural gas burns cleaner than other fossil fuels such as coal or oil, it is still a non-renewable source of energy. Our continued reliance on this source of energy may threaten our energy security or independence in the future. Therefore, it is imperative to employ more renewable sources of energy, such as PV.

1.3 Solar Electricity

The sun is the ultimate energy source. In fact, the energy stored in the fossil fuels we burn originated from the sun from back when they were formed. Directly harnessing the sun's energy for electricity generation provides numerous advantages. Some of the technologies involved with solar electricity generation include solar photovoltaic as well as concentrated solar power (CSP). Solar photovoltaic technology utilizes arrays of panels with photovoltaic cells to convert the sun's energy into electricity; on the other hand, CSP technology utilizes arrays of mirrors which concentrate the sun's radiation on either one point or in a line, convert that into thermal energy, which can then be converted to electricity (Zweibel et al 2007, 66-72). Solar thermal technologies typically utilize a tracking system, while photovoltaic systems can also use fixed axis systems.

The potential of solar as an electricity source is immense. The only caveat is that solar electricity requires a lot of open land, which, luckily, the United States possess. Researchers estimate that converting only 2.5% of the incoming solar energy per year on the 250,000 square miles of land in the Southwest United States would be enough to match the nation's total energy consumption in 2006 (Zweibel et al 2007, 64).

1.4 Solar Technologies

This section will discuss the different solar technologies used in solar electricity generation. This includes both photovoltaic technologies as well as thermal technologies. Determining the technology used for generation was critical in the site suitability analysis.

1.4.1 Photovoltaic Technologies

The first type of solar technology is the solar photovoltaic systems. For this thesis, fixed-axis ground mounted photovoltaic panels are studied. PV systems convert solar radiation into electricity via the photovoltaic effect. In simple terms, the photovoltaic effect is defined as the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto it (Goetzberger et al. 2002, 2). Photovoltaic devices typically use a p-n junction within a semiconductor to create the voltage. A cross section of a typical solar cell is illustrated below in Figure 1:

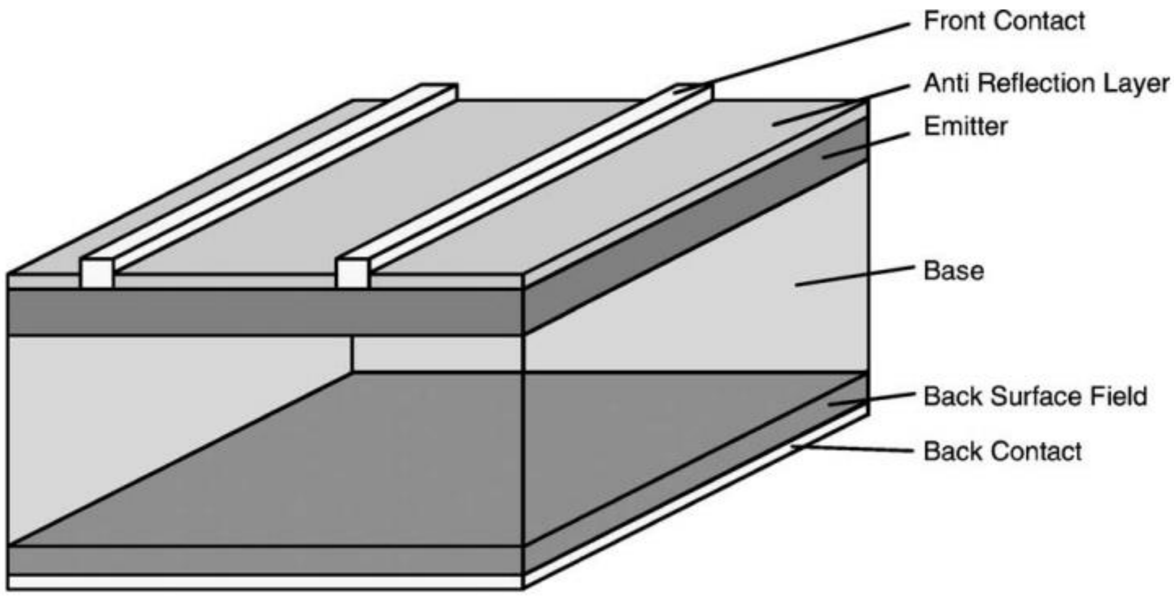

Figure 1 Solar photovoltaic cell cross section. *Source*: Goetzberger et al. 2002

The first silicon photovoltaic cell was made by Bell Laboratories in 1954, and only had an energy conversion efficiency of 6%, which has about tripled by 2015 (Goetzberger et al. 2002, 2, Green et al. 2014). Efficiency has always been an issue with solar photovoltaic technology, and with increased efficiency, the potential of solar photovoltaic technology becomes greater. Solar cells were initially used in space vehicle power supplies, but with increasing efficiency, photovoltaics have found applications in many areas such as utility-scale and residential scale generation.

1.4.2 Solar Thermal Electric Technologies

Solar thermal electric facilities are also known as concentrating solar power systems. These are typically large scale generation systems which gather the heat generated from sunlight to convert water into steam (Gabbard 2011, 5). These systems work by using an array of mirrors to concentrate sunlight onto a focal point or line which is usually a tube or hose of water, oil, or molten salt.

There have been three general types of CSP systems in use as of 2011: parabolic trough systems, heliostat systems, and dish systems. The parabolic trough system uses a long parabolic reflector array that focuses sunlight onto a line where a thin tube is placed with the water, oil, or molten salt (Gabbard 2011, 5). An example of this is the Solar Energy Generating Systems, located in the Mojave Desert, California (also known as Ivanpah), which boasts as the largest solar electricity facility worldwide as of 2011, with a generating capacity of up to 353 MW (Gabbard 2011, 5). The heliostat, also known as the power tower system uses flat mirrors placed around a single tall tower. These mirrors focus sunlight at a point at the top of the tower, where the water is converted instantly into steam. There are not many heliostat systems that exist, though there are many worldwide which are under construction. An example of a heliostat system is illustrated below in Figure 2:

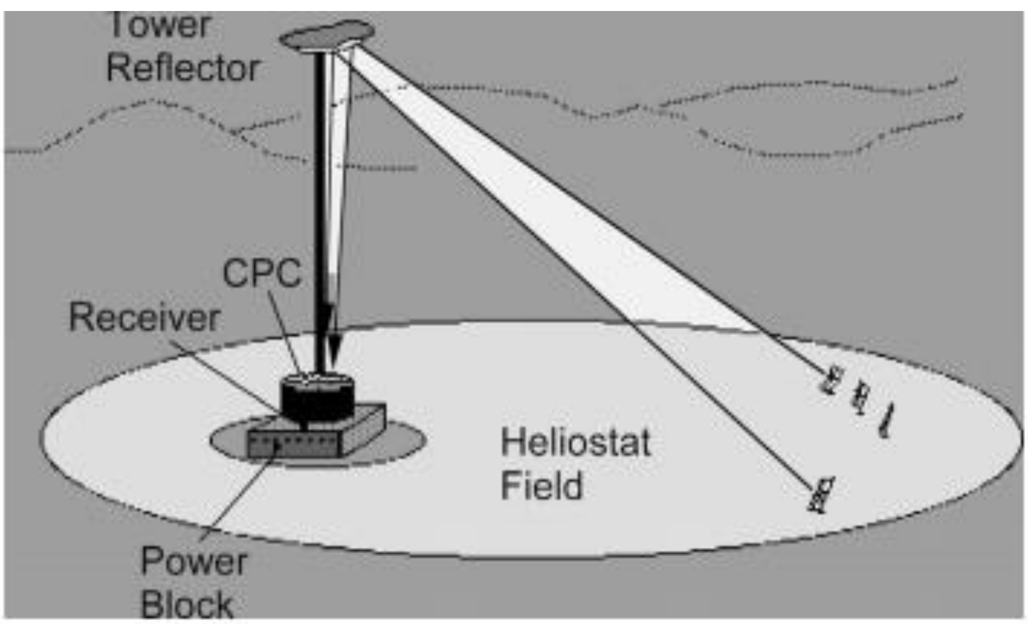

Figure 2 Heliostat schematic *Source*: Buck and Pacheco 2002

The third type, the dish system, uses a parabolic receiving dish, much like a satellite, to collect heat at the focal point in a dish, where the water is converted to steam to generate electricity (Gabbard 2011, 6).

1.5 Rationale for Solar Development on Agricultural Land

This thesis focuses on land with agricultural uses due to their wide open, flat land characteristics. On top of that, choosing these rural agricultural lands for renewable energy development can create jobs and opportunities in these rural areas, reducing the global trend of migration towards urban areas (Panwar et al. 2011, 1514). The current trend of people migrating to urban areas has been causing problems in pollution, congestion, as well as sanitation. Not only will the energy generated be cleaner, but bringing jobs outside of the urban environment can also help to alleviate these problems associated with urbanization. Being able to harvest this renewable energy in a decentralized fashion (unlike fossil fuels), will allow us to sustainably and reliably meet rural and small-scale energy demands (Panwar et al. 2011, 1514).

Furthermore, according to a publication by the Building Research Establishment (BRE) of the United Kingdom (a private consultant that works with both the private sector as well as the government on the built environment sector), Ground Mounted Solar PV projects over 50 kW (or 0.05 MW) should ideally utilize previously developed land, brownfield land, contaminated land, industrial land, and agricultural land (BRE 2013, 5). Agricultural lands are generally wide open areas with relatively large areas as well as a level terrain. These all make for an ideal setting for ground mounted solar PV systems. Fresno County is rich in agricultural lands, many of which can be for their solar resources to produce clean electricity.

1.6 Structure of this Document

The rest of this document begins with a discussion of past related work in solar PV development in Chapter 2. Following, Chapter 3 outlines the study area and data sources, while providing a detailed description of the methodology used for this thesis. Chapter 4 discusses and illustrates the results from the various steps of the methodology for this thesis in both the pre-screening steps as well as the raster analysis steps. Finally, this document closes with Chapter 5, discussing key observations and their significance, as well as outlining any potential areas of improvement for future work.

Chapter 2 Background & Related Work

This chapter discusses some of the information most relevant to the solar PV development field. Furthermore, it also draws upon past researchers' works and discuss how they may have influenced or are incorporated into this thesis.

2.1 Background

As the population of California continues to grow, so does the energy demand. According to a 2012-2022 Energy Demand Forecast spreadsheet provided by California Energy Commission (CEC) (Energy Information Administration 2012), the net peak demand for a mid-demand case scenario in 1990 was 47,546 MW. This grew to 60,310 MW in 2011, and is projected to grow to 69,148 MW by 2020. This accounts for roughly a 45% increase in energy demand over the course of 30 years. In order to meet this demand, we must continue to find ways to expand our energy production capacity.

As a vehicle-centric state, California not only has high energy needs, but also inherits a severe emissions problem. Furthermore, due to recent concerns with Global Climate Change and the limited fossil fuel resources available to us, politicians such as Governor Brown have signed legislation requiring California to meet a goal of 33% energy generation from renewable sources by 2020. California is blessed with a vast amount of solar resources at its disposal. In fact, as of 2014, California had 10,695 MW of solar generating technologies installed, which accounted for roughly 17% of California's total energy demand for 2014 according to the CEC's Energy Demand Forecast Spreadsheet (Solar Energy Industries Association 2014; Energy Information Administration 2012). Solar resources should be further investigated so that we can unlock and tap into these renewable, environmentally-friendly resources to satisfy our huge appetite for energy.

This thesis is aimed at identifying suitable sites for small-scale PV solar plants. Small-scale PV plants are classified by the National Renewable Energy Laboratory (NREL) as between 1-20 MW in generation capacity (Ong et al. 2013, V). These smaller plants make for cheaper development costs, faster build times, and more decentralized energy generation. There may be additional costs associated with installing ground-mounted panels on slopes greater than 5% (Macknick et al. 2013, 11). Thus only parcels with less than 5% slope are considered. Furthermore, as mentioned previously, according to the BRE ground mounted solar PV projects should utilize previously developed land, brownfield land, contaminated land, and agricultural land (BRE 2013, 5). For my thesis, I have chosen to focus solely on agricultural land due to the relatively obstruction-free nature of this land-use.

2.2 Related Works

Numerous researchers have already performed similar or related analyses on PV site suitability in other regions. However, each employ different methods, all of which have been put into consideration in completing this thesis. It is important to examine what other researchers did and see what methods worked for them, to learn from how they went about identifying suitable sites for solar PV farm development. It is also helpful to see how they conducted their research and why they chose their methods, to help develop and justify my own methodologies.

2.2.1 Multi-Criteria Evaluation

Yassine Charabi and Adel Gastli's paper, *PV Site Suitability Analysis using GIS-Based Fuzzy Multi-Criteria Evaluation*, uses a multi-criteria evaluation approach to identify suitable areas for solar PV farm development in Oman (Charabi and Gastli 2011). In their study, the researchers use both a Boolean overlay and weighted summations approach, coming up with criteria weights through selection, the Fuzzy Logic Ordered Weight Averaging (FLOWA) analysis tool in ESRI's ArcMap 9.3, and an hierarchical structure (Charabi and Gastli 2011, 2557). They generated three layers: a solar radiation layer, generated from the solar radiation analyst tool in ArcGIS 9.3; a constraints layer, showing a DEM of the area and exploitable land area based on geography; a distance to major roads layer, showing the distance of each point as a raster, from the closest road (Charabi and Gastli 2011, 2558). All these layers were then used in the FLOWA analysis to generate a map showing land suitability levels for solar development, as illustrated in Figure 3. It is important to note that the output in Figure 3 is similar to the output for this thesis. What is particularly relevant about this study is the researchers' use of a multi-criteria approach, and the criteria they chose as part of their suitability analysis.

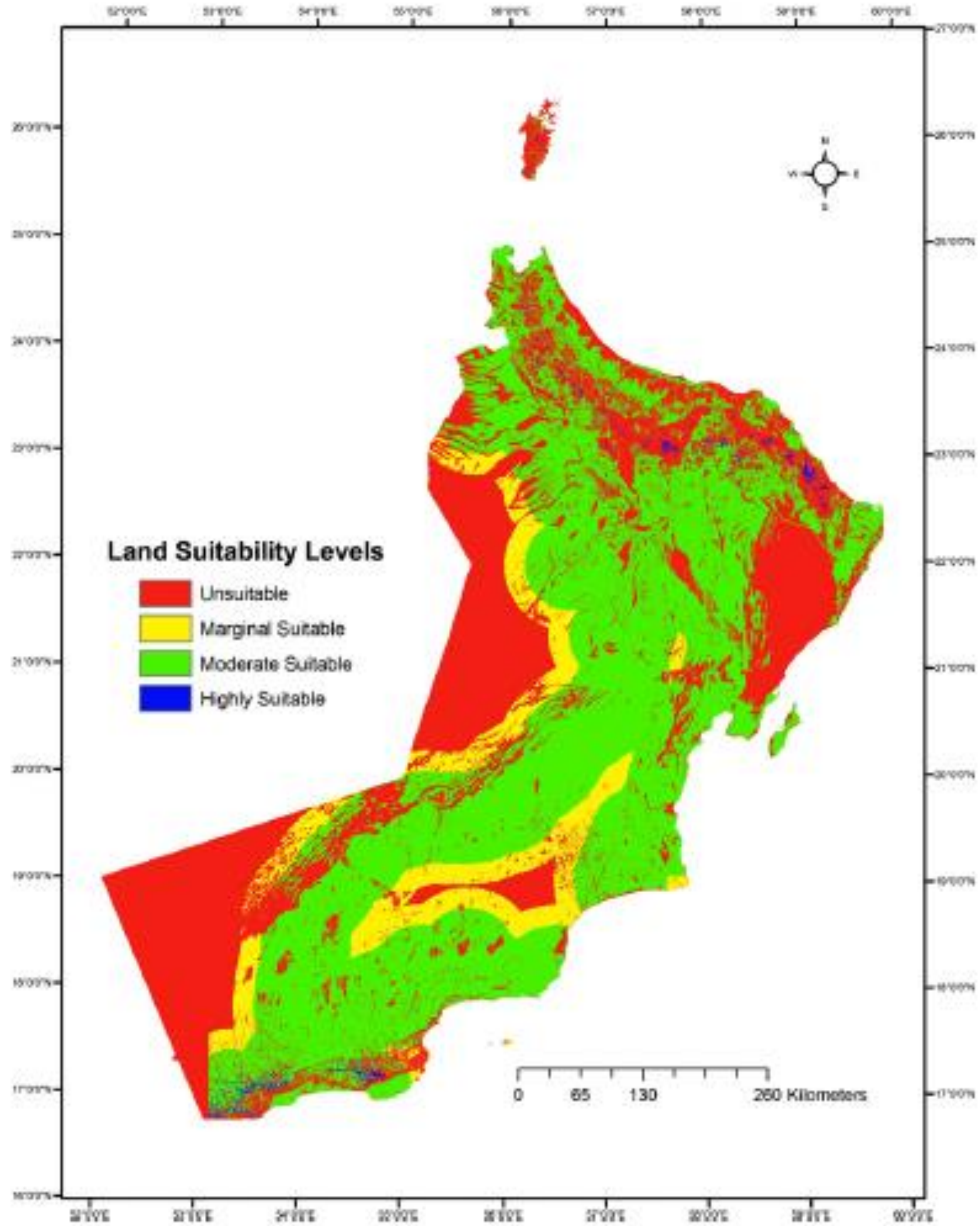

Figure 3 Spatial distribution of land suitability levels *Source*: Charabi and Gastli 2011

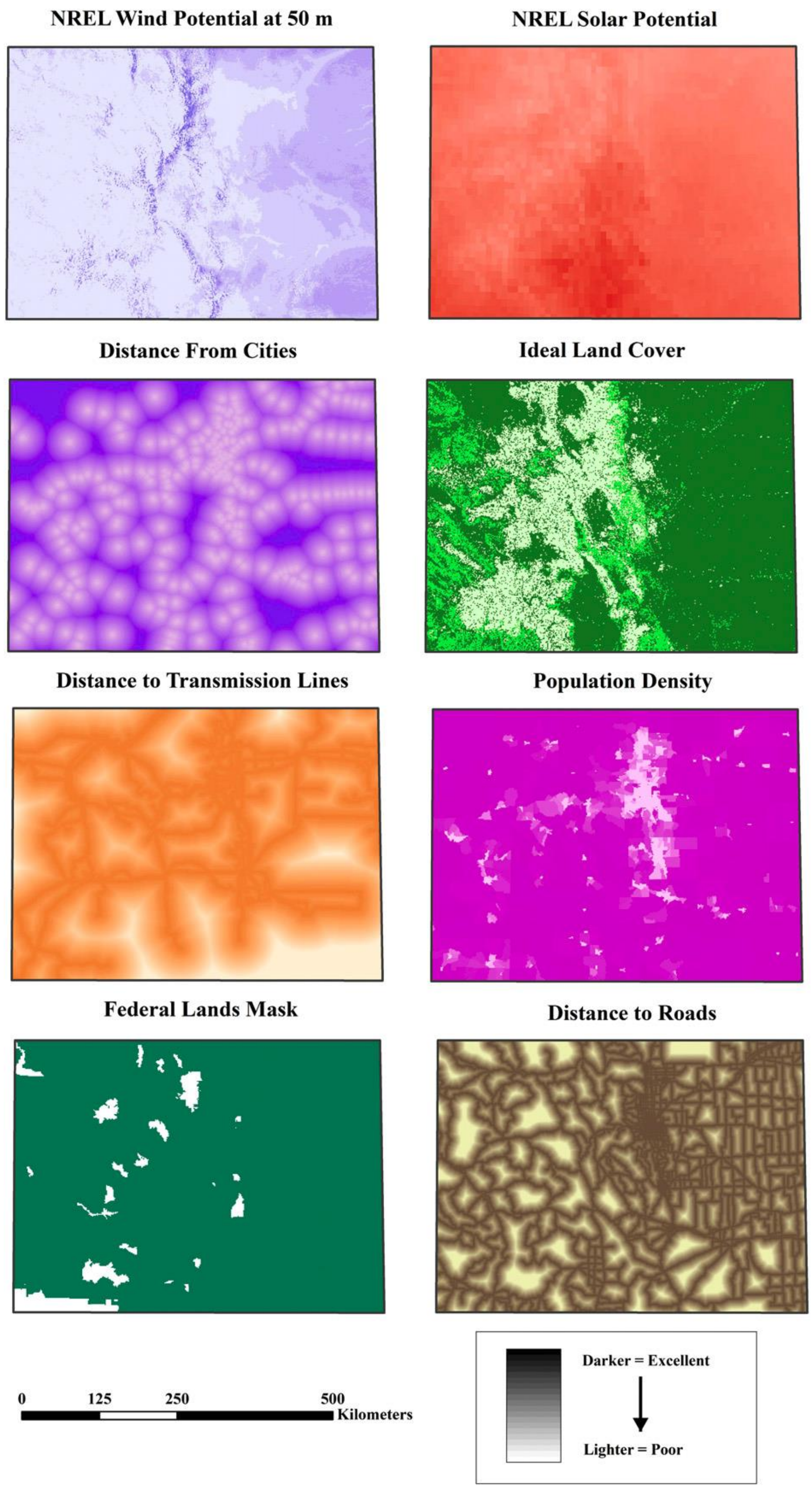

Figure 4 Sample of criteria used for solar and wind suitability modeling *Source*: Janke 2010

Another scholar, Jason R. Janke (2010) also uses multi-criteria modeling in his study *Multicriteria GIS Modeling of Wind and Solar Farms in Colorado*. In his study, Janke uses a multi-criteria (which considers land cover, population density, federal lands, distance to roads, distance to transmission lines, and distances to cities) approach to model both wind and solar farms in Colorado. The multi-criteria and weighting system and reclassification of land cover, population density, federal lands, distance to roads, transmission lines, and cities according to their suitability are particularly relevant to my study due to their use of multi-criteria modeling. For the solar insolation data, they used solar radiation data from the NREL, at a 40 km resolution. In essence, the author reclassified all the data and rasterized them so he could assign weights, and scored the land based on the criteria they chose, as illustrated above in Figure 4.

2.2.2 Modeling Solar Radiation

Modeling solar potential is part of the process to modeling solar PV site suitability. In his study, *Modelling of Solar Energy Potential in Nigeria Using an Artificial Neural Network Model* (2009), Fadare develops an artificial neural network (ANN)-based model to predict solar energy potential in Nigeria. According to Fadare, an ANN is a branch of artificial intelligence belonging to a group of algorithms called connectionist models, by using inputs, weights and biases, summing junctions, and transfer junctions, Fadare bases his model off of this ANN model and generates many contour maps predicting solar energy potential in kWh/m^2-day, across Nigeria (Fadare 2009, 1411).

One of the more dated models that have been used in the past is SOLARFLUX, which was employed in a study by Dubayah and Rich (1995). SOLARFLUX uses the input of a rasterized elevation surface, along with latitude, time interval, and atmospheric values to provide an output of radiation flux, duration of direct radiation, sky view factor, hemispherical projections of horizon angles, and diffuse radiation flux for each location (Dubayah and Rich 1995, 413). These outputs are very similar to what Esri's Area Solar Radiation Tool produces, which are discussed in the following subsection.

2.2.3 Esri's Area Solar Radiation Tool

In a thesis written by a past USC Spatial Sciences Institute graduate student, Devon Munsell (2013) estimates the solar potential of closed landfills across California. In his study, Munsell samples a list of closed landfills in California based on specific site characteristics including landfill closing dates, location accuracy, land area, distance to transmission lines, and distance to graded roads (Munsell 2013, 41). He then used Esri's Area Solar Radiation tool to estimate the solar irradiance on these sites, which he then used to estimate potential energy production with statistics and mathematical formulas such as Boolean Slope and Aspect (Munsell, 2013, 48-50). Esri's Area Solar Radiation tool is a powerful tool that allows the user to analyze elevation data and estimate direct and diffuse or global radiation values for different time intervals and ranges, latitude and resolution (Fu and Rich 1995). Munsell's study is particularly relevant because I also employ Esri's Area Solar Radiation tool to visualize and score solar potential on suitable lands for PV development.

Today, the Area Solar Radiation tool available in Esri's ArcGIS is commonly used in studies geared towards various types of solar analyses. This tool essentially uses an input DEM or some elevation raster, to derive incoming solar radiation values based on various inputs from the user, which will be discussed further in the Methodology section of this thesis. It also allows for the user to customize the specific latitude values, sky size or resolution, time(s) during a particular year, as well as topographic parameters and radiation parameters. In terms of the final outputs, it creates a global radiation raster, as well as optional direct/diffuse radiation and direct duration rasters.

From the past research, it is evident that multi-criteria evaluation is a popular technique employed when it comes to solar site suitability studies. This sets the impetus for this thesis to further investigate a multi-criteria approach, while being able to break up and study each individual layer. Using various sets of ArcGIS tools including Esri's Area Solar Radiation tool alongside a multi-criteria approach, this thesis aims to develop its own approach to this topic. In doing so, it will allow for future researchers, government decision makers, and solar developers to study this thesis as a model or guide for their own purposes.

Chapter 3 Data and Methods

This chapter discusses the various methods that have been used to conduct the site suitability analysis. This chapter covers the study area, data sets and sources, as well as the data processing needs that are required for the completion of this thesis. The goal of this is to identify suitable sites for small-scale fixed-axis ground mounted PV solar farms in Fresno CA. The second segment of this thesis aims to score the identified parcels by suitability based on factors such as distance to roads, slope, or solar insolation.

3.1 Study Area

The study area in this thesis is focused in Fresno County, California. Fresno County is located in Central California, near the center of California's San Joaquin Valley. The Coast Range foothills form the County's western boundary, while the Sierra Nevada forms the eastern boundary. Fresno County is one of the largest, fastest growing counties in California, boasting as the 10^{th} most populous county in California with an estimated 917,515 residents (The County of Fresno). Fresno County consists of 15 incorporated cities, and is one of the most productive agricultural counties in the United States. Much of the land in Fresno is dedicated to agricultural uses, which primarily consists of flat, open and unobstructed land, making for suitable sites for solar PV installation. The boundaries for the study area are defined by the outer boundaries of Fresno County, as illustrated below in Figure 5.

Figure 5 Boundary of study area

3.2 Data Sources

This section describes the various geospatial data and their sources used in this PV solar farm site suitability analysis. The following is a table including the data sources and information about them.

Table 1 Data sources

Dataset	Data type	Description	Source	Date
Parcel	Polygon	Represents all individual parcels in Fresno County	Fresno County	Estimated December 7, 2014
Zoning	Polygon	Represents all zoning designations in Fresno County	Fresno County	Estimated December 7, 2014
Street	Line	Represents all road infrastructure in Fresno County	Fresno County	Estimated December 7, 2014
Transmission	Line	Represents all transmission infrastructure in Fresno County	Devon Munsell (FEMA)	1993
California Conservation Act	Spreadsheet	Tabular data relating parcel APNs and California Conservation Act status.	Fresno County	July 27, 2015
Elevation	Raster	DEMs used to calculate slope and solar insolation	USGS	2013

3.2.1. Parcel Data

The parcel data polygon shapefile was downloaded from the Fresno County GIS website. Fresno County makes GIS information available to the public in the form of maps, reports, and charts. Through this service, Fresno County offers government information based on geographic location.

The dataset, named *Fresno_Parcels*, includes boundaries for all parcels within the County limits of Fresno. This dataset is projected in the NAD 1983 State Plane California IV coordinate system, with a linear unit of feet. The *SHAPE_AREA* field in this dataset will be of particular interest in the pre-screening portion of the methodology for this thesis to determine overall parcel size.

3.2.2. Zoning Data

The zoning data polygon shapefile was also downloaded from the Fresno County GIS website. The dataset, named *Fresno_Zoning*, includes zoning designations for the areas of Fresno County. The outer boundary of this dataset defines the study area for this thesis. This dataset is projected in the NAD 1983 State Plane California IV coordinate system, with a linear unit of feet. The *ZONING_DESIGNATION* field is of particular interest in the pre-screening portion of the methodology for this thesis to determine agricultural land use.

3.2.3. Street Data

The streets data line shapefile was also downloaded from the Fresno County GIS website. The dataset, named *Fresno_Streets*, provides information on the street networks of Fresno County. This dataset is also projected in the NAD 1983 State Plane California IV coordinate system, with a linear unit of feet. This dataset is used in this thesis to create a distance raster, buffer, as well as a mask to identify parcels within ideal distances from streets.

3.2.4. Transmission Data

The transmission line data shapefile was retrieved from a past USC GIST student, Devon Munsell, who used it in his thesis, *Closed Landfills to Solar Energy Power Plants: Estimating the Solar Potential of Closed Landfills in California* (2013). According to the source used in Munsell's thesis, the National Renewable Energy Laboratory no longer supports this shapefile, and has asked the distributor to remove it. This may bring the accuracy or reliability of the data into question. However, to acquire a set of transmission line data from a private company costs far more than is desirable for the budget of this thesis.

This dataset was originally created by the Federal Emergency Management Agency in 1993. The data represents a schematic of transmission line connectivity and the network throughout California.

3.2.5 California Conservation Act Data

A dataset in tabular database format was acquired by contacting Fresno County GIS Department. This dataset lists all the parcels in Fresno County as well as fields for contract number, contract year, and non-renewal year. Though no specific date was given for the creation or last update of the data, the dataset includes dates as recent as 2014. This dataset was used to identify only agricultural parcels that were not under a California Conservation Act Contract with the government, and thus would be viable for solar farm development.

3.2.6. Elevation Data

The DEMs were acquired as 9 separate raster files for the various communities that make up Fresno County and more, at a spatial resolution of 1 Arc Second. This data was retrieved from the USGS National Map Viewer website. The USGS National Mapping Program aims to meet the nation's geospatial needs by ensuring access to and advancing application of these data.

3.3 Methodology

This section outlines the steps taken to complete the solar site suitability analysis for this thesis. A general outline for the workflow of this methodology section is illustrated below in Figure 6.

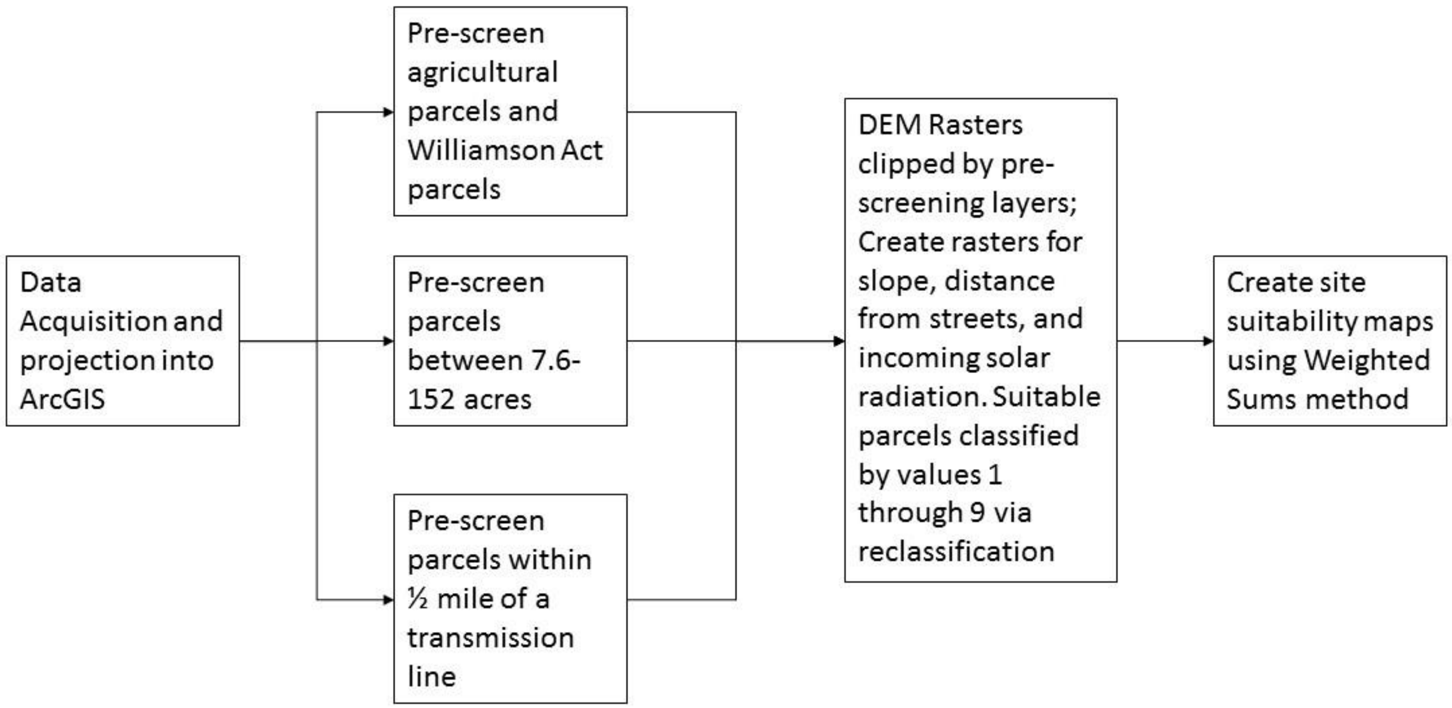

Figure 6 Project flowchart

3.3.1. Pre-screening

The first few steps consisted of pre-screening the datasets for various criteria including, agricultural parcels, parcel size, streets, and transmission lines.

3.3.1.1. Agricultural Parcels

I began with the zoning and parcels datasets. There are a total of 290,811 parcels in Fresno County in the parcels dataset. According to Gazheli and Corato (2013, 508) ground-based PV plants require a large area land surface for the installation of solar panels and are therefore present in areas traditionally designated for agriculture. Thus, I decided that my first pre-screening step should be to identify just the agricultural parcels in Fresno County. By using the following Standard Query Language (SQL) statement with the Select by Attributes Function in ArcGIS, Fresno County was pre-screened for compatible land uses including agricultural, exclusive agricultural, limited agricultural, and general agricultural:

ZONING_DES = 'Agricultural' OR ZONING_DES = 'Exclusive Agricultural' OR ZONING_DES = 'Limited Agricultural' OR ZONING_DES = 'General Agricultural'.

The Intersect function was then used to identify all the parcels from the Fresno_Parcels dataset that spatially intersect with these compatible land uses.

3.3.1.2. Parcel Area

The next step was to identify those parcels that had the necessary area to develop a "small" sized PV solar farm, defined by the NREL as between 1-20 MW in generating capacity (Ong et al. 2013, V). The NREL estimates that the capacity-weighted average land use for a fixed axis small PV plant is about 7.6 acres per MWac (Ong et al. 2013, V). This translates to an area of between 7.6 acres and 152 acres for a fixed axis PV farm with a capacity of between 1-20 MW. The units for the Shape_Area field is given in square feet. Since 1 acre is 43,560 square feet, the parcels to be identified were going to be between 331,056 square feet and 6,621,120 square feet. As in the previous step, the Select by Attributes function was used with the following SQL statement to identify these parcels:

Shape_Area > 331056 AND Shape_Area < 6621120

The resulting layer was then exported as a shapefile to represent all parcels between 7.6 acres and 152 acres, which are designated for agricultural use.

3.3.1.3. California Land Conservation Act Parcels

The California Land Conservation Act, commonly referred to as the Williamson Act, was passed by the California Legislature in 1965 in an attempt to preserve agricultural and open space lands (California Department of Conservation 2015). The Williamson Act allowed for agricultural land owners to receive tax cuts in exchange for a binding contract to maintain their land strictly for agricultural and open-space land uses (California Department of Conservation 2015).

For this pre-screening step, the tabular dataset acquired from the Fresno County GIS department was joined to the resulting dataset from the previous step by the APN field. Next using a combination of an SQL statement in the Select by Attributes function, as well as manually selecting parcels, I was able to select only parcels that were never or no longer under a Williamson Contract with the government, and export this as a shapefile. The SQL statement I used in combination with manual selection is as follows:

NON_RENEWAL <> " "

Where NON_RENEWAL denoted the year during which a parcel entered a non-renewal contract with the local government, releasing it from a previous Williamson Act Contract. Empty fields, " " denoted parcels that have been and are bound by a Williamson Act Contract. The rest of the parcels, which included parcels that never entered a Williamson Act Contract, had null values for this field, as well as the Contract Year and Number fields, and could not be selected by SQL. Therefore, parcels which never entered a Williamson Act Contract were added to the selection manually. The resulting data layer was a shapefile which represented all agricultural parcels between 7.6 acres to 152 acres, which were no longer or never bound to a Williamson Act Contract with the local government.

3.3.1.4. Transmission Lines

The next step was to pre-screen the data for areas with access to the transmission line networks of Fresno County. According to the NREL, generally, transmission lines need to be within a0.5 mile distance of a solar facility (Brown et al. 2013, 21). Thus, the *Trans_Grid_FEMA* dataset was used to create a 0.5-mile buffer with the Buffer function in ArcGIS, to identify all areas within a 0.5-mile distance from a transmission line. First, because the *Trans_Grid_FEMA* dataset contained data on the entire state of California, the Clip function was used to cut down the dataset to just include transmission lines within the study area. Next, as with the streets data, I used the Identity function in ArcGIS to identify intersections between the Trans_Grid_FEMA_Buffer and the resulting output in Figure 13, while preserving the identity of both original datasets. I made sure to select “ALL” for the Join Attributes dialog box, and used the *Trans_Grid_FEMA* dataset as the identity feature. Again, using the Select by Attributes function on the dataset resulting from the Identity function, the following SQL statement was used to filter out all parcels that didn’t intersect:

FID_Trans_Grid_FEMA_Clip_Buffer <> *-1*

This identifies those parcels which are within a 0.5 mile distance of a transmission line. The resulting data layer was a shapefile which represented all agricultural parcels between 7.6 acres and 152 acres, not under a Williamson Act Contract, and within 0.5 miles of a transmission line.

3.3.2 Raster Pre-Processing

The DEM data was pre-processed before inputting it into Esri's Area Solar Radiation tool in the following step. First, all 9 tiles were mosaicked into one single raster by using Esri's Mosaic to New Raster tool in ArcGIS 10.2. The new output from the Mosaic to New Raster tool was clipped by shapefile of the resulting output from the pre-screening section of this thesis. The resulting output is illustrated below in Figure 7.

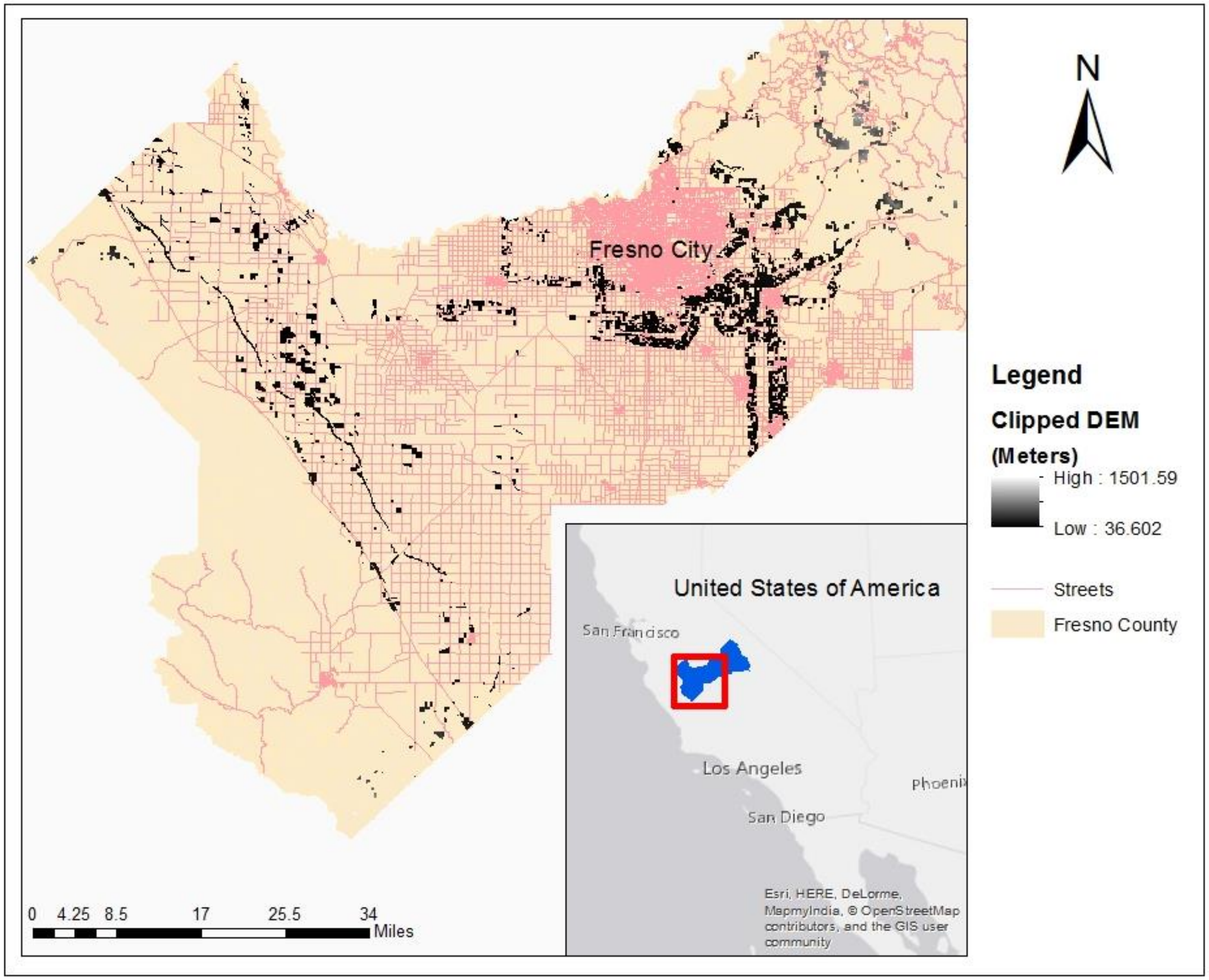

Figure 7 Mosaicked DEMs clipped by pre-screening layer

3.3.3. Solar Analyst

Esri's Area Solar Radiation tool allows the user to output radiation rasters in the form of floating-point types in the units of watt hours per square meter (WH/m^2) (Esri 2013). This tool is a complex tool which allows the user to characterize incoming solar radiation by selecting an input raster to create an output global radiation raster. A global radiation raster is defined as the total amount of incoming solar insolation, both direct and diffuse calculated for each location (Esri 2013). According to Munsell (2013), photovoltaic systems take advantage of global radiation, thus, only the global radiation raster was selected for this step. Esri also provides for many optional inputs in this tool including latitude, sky size or resolution, time configuration, day interval, hour interval, topographic parameters (each interval, Z factor, slope and aspect input type, and calculation directions), radiation parameters (zenith divisions, azimuth divisions, diffuse model type, diffuse proportion, and transmittivity), and optional outputs (direct radiation raster, diffuse radiation raster, and direct duration raster).

The latitude option allows the user to input the approximate latitude of the site area. This option is designed for local landscape scales, so it only takes one latitude value for the whole DEM (Esri 2013). Due to the local scale of this thesis, selecting a value for this is very helpful. Esri's Area Solar Radiation tool automatically calculates this value.

The sky size or resolution option allows the user to configure the resolution of the output raster from this tool. The default value is set to 200 (sufficient for whole DEMs with day intervals of greater than 14 days), which creates a raster of 200 by 200 cells (Esri 2013). A value of 512 is sufficient for calculations at point locations where calculation time is less of an issue, and at day intervals of less than 14 days, and when the day interval is equal to one, values of 2800 or higher are recommended (Esri 2013).

The time configuration option allows for the user to define a date range during which the solar analysis takes place. This option allows for a maximum number of days to be 365 days, or a year (Esri, 2013). For this thesis, the entire year of 2015 was selected.

The day interval option allows the user to input the time interval in days used for calculation of sky sectors for the sun map. Day intervals greater than three are recommended due to sun tracks overlapping at lower intervals (Esri 2013). Furthermore, for calculations of the whole year with monthly interval, the interval option is disabled and instead a monthly interval is used (Esri 2013). Similarly, the hour interval allows the user to input the time interval during the day used for the calculation of sky sectors for the sun map (Esri 2013). For this step, Esri suggests a small day interval, accompanied by a large sky size of 2800 or more (Esri 2013). Therefore, the smallest recommended day interval of four was selected, since sun tracks tend to overlap over three days. To accompany this short day interval, a large sky size of 2800 was selected, as suggested by Esri.

The each interval checkbox allows the user to specify whether or not to calculate a single total insolation value for all locations or multiple values for the specified hour and day intervals (Esri 2013). For this thesis, the primary focus is the overall incoming solar radiation over a year, so this checkbox is not selected.

The Z-factor option allows the user to input the number of ground (x,y) units within a z-surface unit. When calculating a surface where the Z units are expressed in units different from the ground x,y units, using the Z-factor is necessary to convert the units and calibrate the tool (Esri 2013). For the DEM used in this thesis, the horizontal distance values were in degrees, while the elevation units were in meters. According to Esri's Desktop Help, data located in latitudes around 40° should use a z-factor of 0.00001171, while data in latitudes of around 30°

should use a z-factor of 0.00001036. Fresno County lies at around 36°N, and so the closest value, the z-factor of for 40° latitude data was selected, 0.00001171.

The slope and aspect input type option allows the user to determine how the slope and aspect information are derived for analysis (Esri 2013). There are two options available in a drop-down menu which include FROM_DEM and FLAT_SURFACE. For this thesis, FROM_DEM was selected because DEM data was used as the input for this step.

The calculation directions option allows for the user to input the number of azimuth directions to use in the analysis. The azimuth is the angle between the point of interest and a reference angle, in this case, true north. The default value of typically, for data with gentle topography, a value of 8 is adequate, and was selected for this thesis (Esri 2013).

The zenith divisions option allows the user to input the number of divisions used to create sky vectors in the sky map (Esri 2013). The zenith is the point in the sky directly above a location on the ground. Generally, a value of 16 or 32 is sufficient for this option; only higher values are required for DEMs with man-made structures in them (Esri 2013). The DEMs in this thesis did not include any man-made structures in them, and thus a low value of 16 was selected.

The diffuse model type allows the user to define the type of diffuse radiation model they would like. The default is the UNIFORM_SKY model, which assumes the incoming diffuse radiation is the same from all sky directions (Esri 2013). The second option, STANDARD_OVERCAST_SKY assumes that incoming diffuse radiation flux varies with zenith angle (Esri 2013). For this thesis, UNIFORM_SKY was selected, which assumes that the skies are generally clear throughout the year.

The diffuse proportion option allows the user to define the proportion of global normal radiation flux that is diffuse, depending on atmospheric conditions. The default value of 0.3 is generally used for clear sky conditions, and was selected for this thesis (Esri 2013).

The transmittivity option allows the user to define the fraction of radiation that passes through the atmosphere. This can be a value between 0 and 1; the default value for a generally clear sky is 0.5, and was selected for this thesis (Esri 2013).

The output selection for direct radiation raster allows the user to select a folder and create a raster characterizing direct solar radiation for the DEM. Likewise, the output selection for diffuse radiation raster and direct duration raster allows the user to do the same with rasters for diffuse solar radiation and direct solar duration (Esri 2013).

Below, Figure 8 illustrates the tools and the various inputs selected for this section.

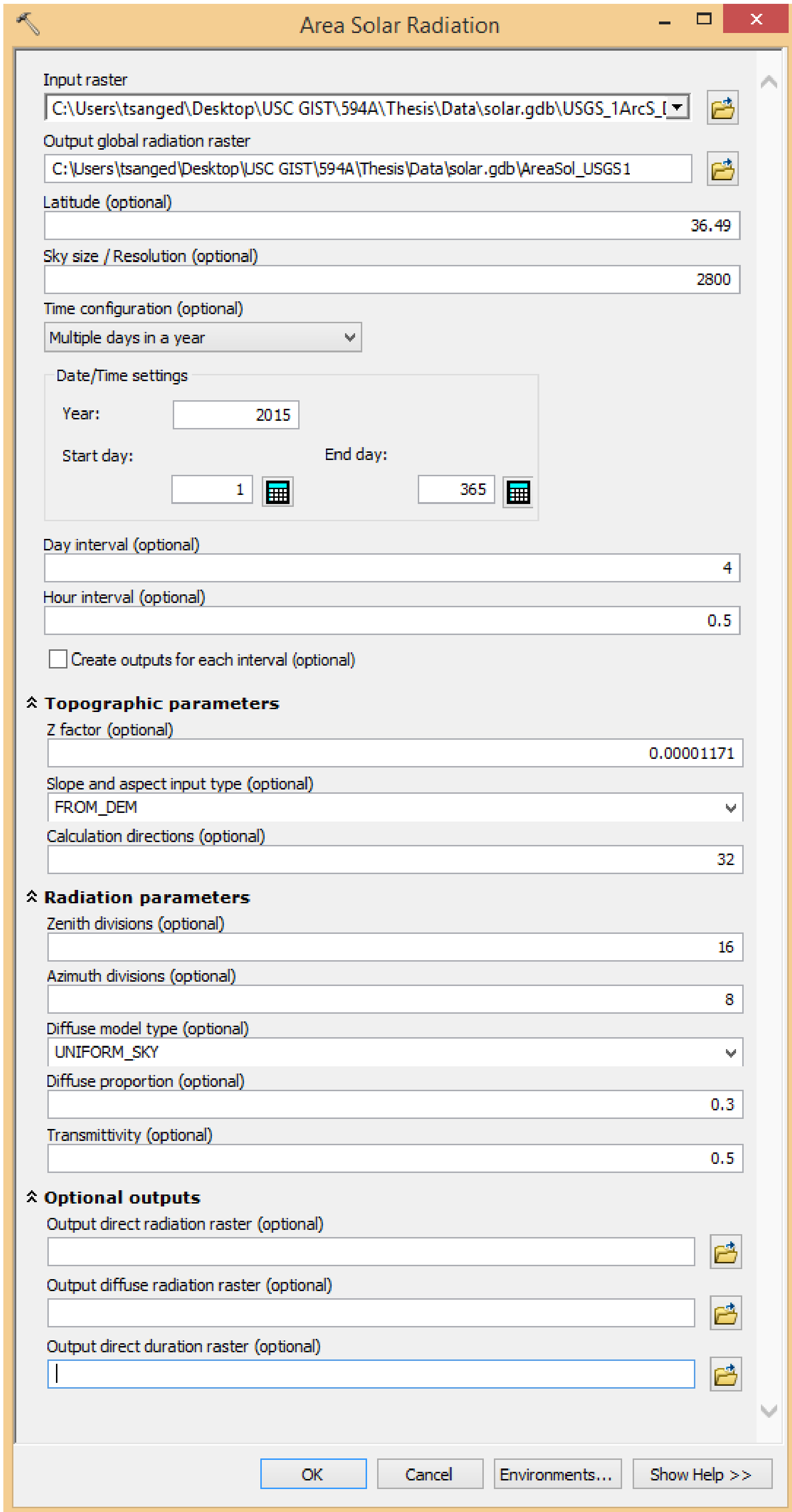

Figure 8 Esri's Area Solar Radiation tool

The DEM data was clipped by the final output of the pre-screening analysis. This clipped raster showing elevations only for those parcels that have fallen within all the pre-screening steps are analyzed. This clipped raster was inputted into Esri's Area Solar Radiation function.

3.3.4. Slope

Selected sites based on the pre-screening analysis are also analyzed for slope. According to Carrion et al. (2008), areas with slopes of more than 3% rise typically are not ideal for grid-connected solar photovoltaic plants. The clipped (by pre-screen criteria) DEM was analyzed with Esri's slope function to illustrate the slopes on each of these parcels, selecting the PERCENT_RISE measurement for the output, as well as a Z factor of 0.00001171 was selected. This produced an output raster illustrating slope of the terrain in percent rise. The following figure illustrates the inputs used for this step.

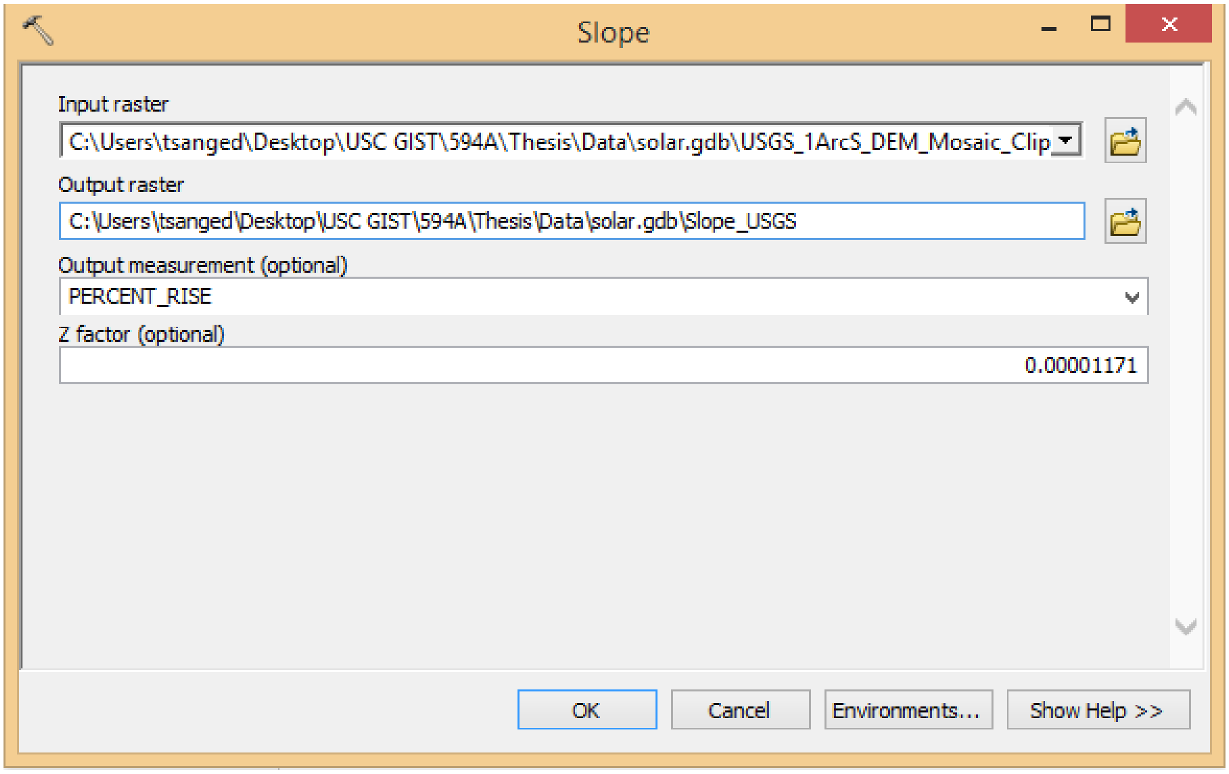

Figure 9 Esri's Slope tool

3.3.5. Distance from Streets

Distance rasters were created from the streets shapefile to score parcels based on distance to these connectors. This was done using the Euclidean Distance function in Esri's ArcGIS 10.2. No maximum distance was selected, as the resulting layer was reclassified to new values, removing data outside the 1-mile criteria from the analyses. This 1-mile buffer criteria was selected based a criteria used in Munsell's (2013) study, where he states that PV facilities should be sited within 1 mile of a road to maximize accessibility. The input values for this step are illustrated below in Figure 10.

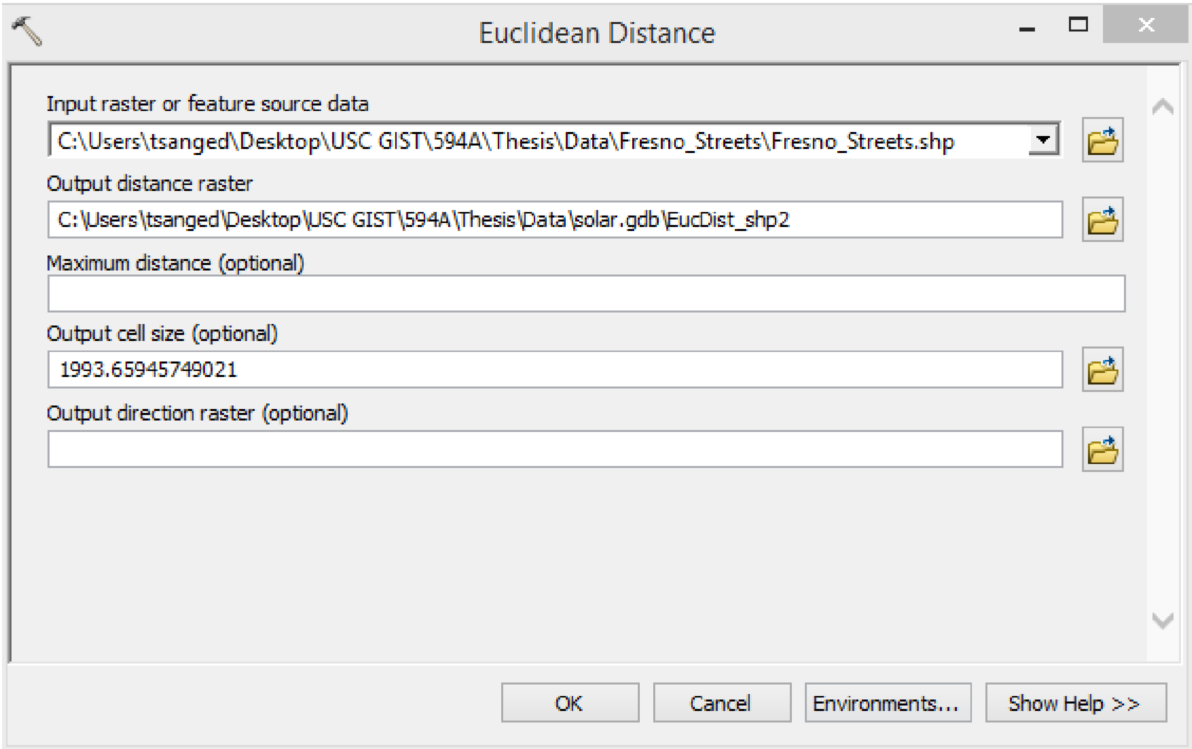

Figure 10 Esri's Euclidean Distance tool

3.3.6. Weighted Sums

The final step of this thesis was to aggregate all three raster datasets which include the slope, direct global radiation, and distance from street rasters, all clipped to the pre-screening layers. For this portion, Esri's Weighted Sums tool was used on reclassified rasters for the three previously mentioned rasters. The Weighted Sums tool works by multiplying rasters and based on location, allowing the user to input weights for each raster (Esri 2013). Reclassifying these datasets first was a necessary step to create a meaningful output from the datasets due to differing units and inverse relations. These rasters were reclassified using an equal interval for each class break, to represent the data as clearly as possible. The slope, distance to road, and global solar radiation values were reclassified as indicated in Tables 2, 3, and 4 respectively.

Table 2 Reclassification values for slope raster

Old Values (% Rise)	New Values
0-0.3	9
0.3-0.6	8
0.6-0.9	7
0.9-1.2	6
1.2-1.5	5
1.5-1.8	4
1.8-2.1	3
2.1-2.4	2
2.4-2.7	1

Table 3 Reclassification values for distance to roads raster

Old Values Distance to roads (Feet)	New Values
0-600	9
600-1200	8
1200-1800	7
1800-2400	6
2400-3000	5
3000-3600	4
3600-4200	3
4200-4800	2
4800-5400	1

Table 4 Reclassification values for Direct Global Radiation raster

Old Values Direct Global Radiation (WH/m^2)	New Values
1,625,314.256944 – 1,756,219.5	9
1,494,409.013889 – 1,625,314.256944	8
1,363,503.770833 – 1,494,409.013889	7
1,232,598.527778 – 1,363,503.770833	6
1,101,693.284722 – 1,232,598.527778	5
970,788.041667 – 1,101,693.284722	4
839,882.798611 – 970,788.041667	3
708,977.555556 – 839,882.798611	2
578,072.3125 – 708,977.555556	1

This gave a highest score of 9 to areas with slopes between 0 and 0.3 percent rise, and the lowest score of 1 to areas with slopes between 2.4 and 2.7 percent rise, 2.7 being the upper limit for parcels being scored. The distance from roads reclassification gave a highest score of 9 for areas between 0 to 600 feet from a road, with an upper limit where the lowest score was given to areas between 4800 to 5400 feet, which translates to roughly 1 mile. Finally, the global radiation raster was reclassified in a similar fashion, however an equal interval classification method was used to divide all value ranges for the dataset into 9 new values, where the highest score of 9 represented areas with the highest global radiation while the lowest score of 1 represented areas with the lowest global radiation. For all data that did not fall within the reclassified value ranges were changed to "No Data", removing these parcels from the study.

Next, with the reclassified rasters where values of 1 were seen as low (worst) scores and values of 9 were seen as high (best) scores, a Weighted Sum analysis was run for the three reclassified datasets. The values for weights are indicated below in Table 5.

Table 5 Weights used for Weighted Sum analysis

Raster	Weight
Reclassified Street Distance	0.5
Reclassified Slope	1
Direct Global Radiation	1.5

Chapter 4 Results

The final outputs of the different portions of this thesis are illustrated and discussed throughout this chapter. Overall, from the pre-screening analysis, the number of parcels in Fresno County for analysis was reduced from 290,811 parcels to 6,412. These parcels were then further analyzed through raster analyses and scored based on a Weighted Sums approach, to identify suitable parcels for small scale thin-film ground mounted solar thin-film PV farms.

The initial goal of this thesis was to create a map illustrating ideal parcels for small scale, fixed-axis solar photovoltaic farms in Fresno County, CA. The outputs illustrated in this chapter each serve a purpose in illustrating these ideal parcels as well as scoring them based on three sets of criteria.

4.1 Outcomes of Pre-screening Analysis

4.1.1 Agricultural Parcels

The first step in illustrating suitable sites for solar PV farm development was to identify parcels with suitable land uses. Due to their wide-open and generally unobstructed nature, this thesis focused primarily on agricultural parcels. Thus, the first step of this analysis was to identify only those parcels which were classified for agricultural use. This initial pre-screening step reduced the number of viable parcels from 290,811 to 49,593 parcels, and created the following outputs, illustrated on separate maps for clarity in Figures 11-15.

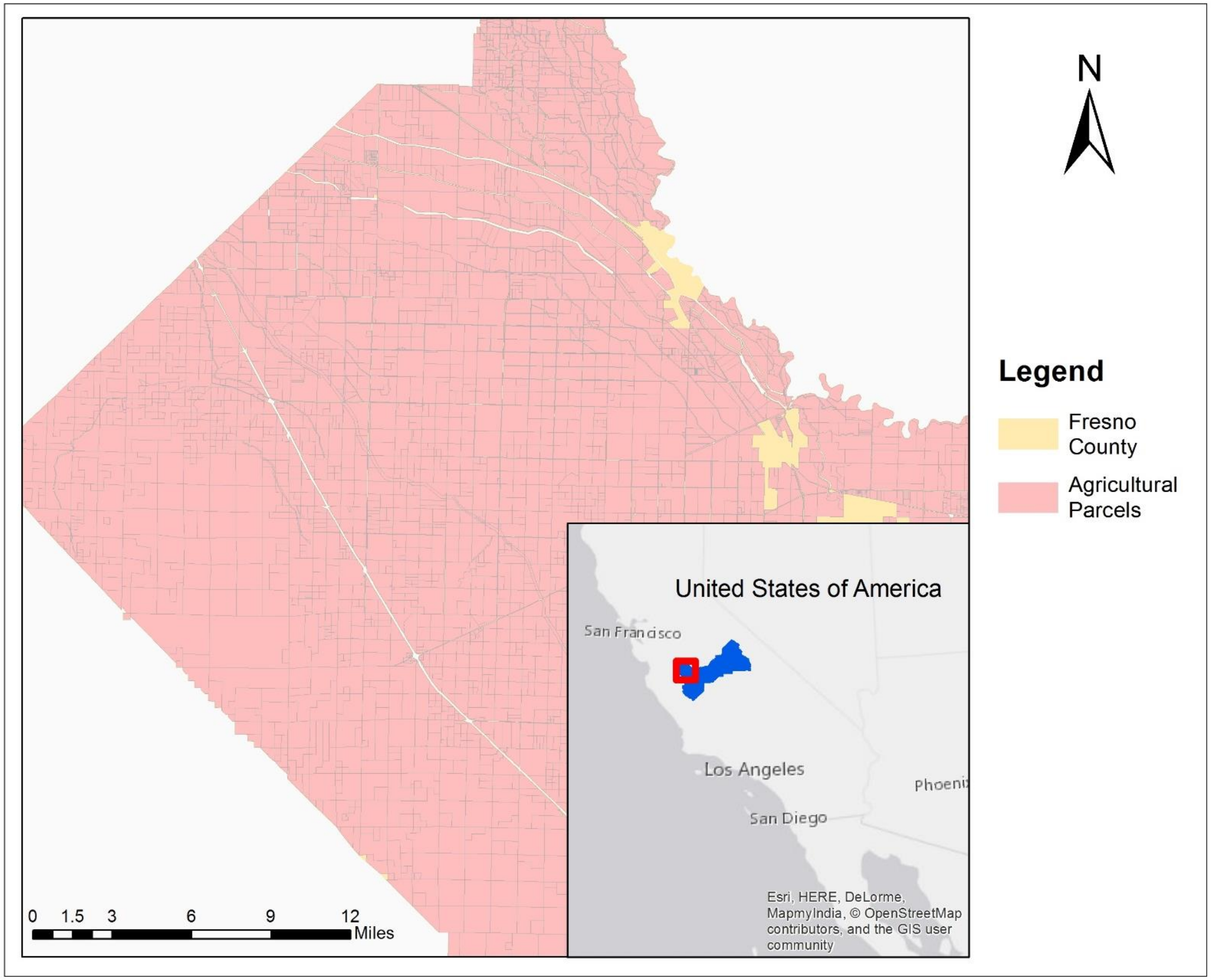

Figure 11 Agricultural Parcels from pre-screening step (Northwest end of Fresno County)

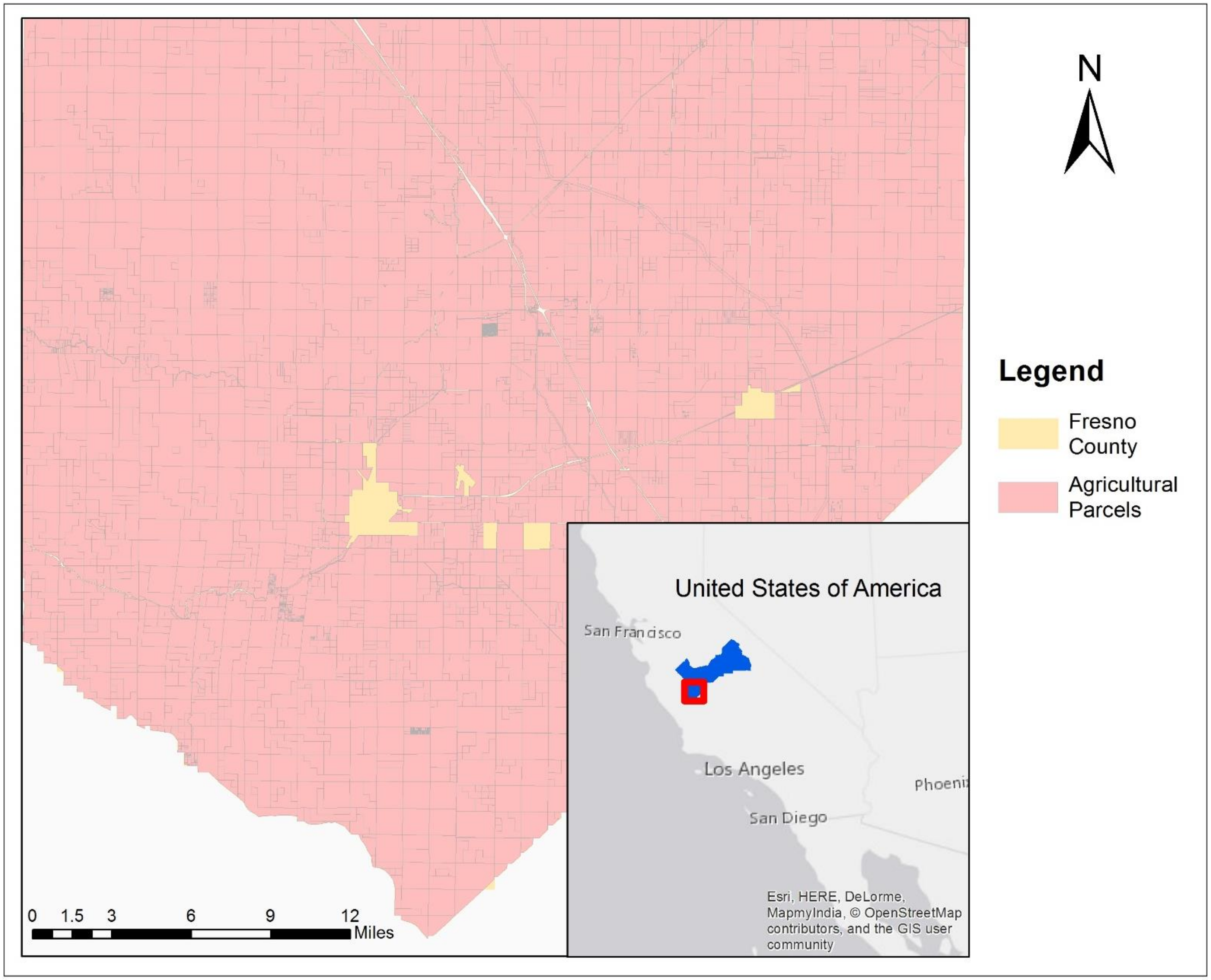

Figure 12 Agricultural Parcels from pre-screening step (Southwest end of Fresno County)

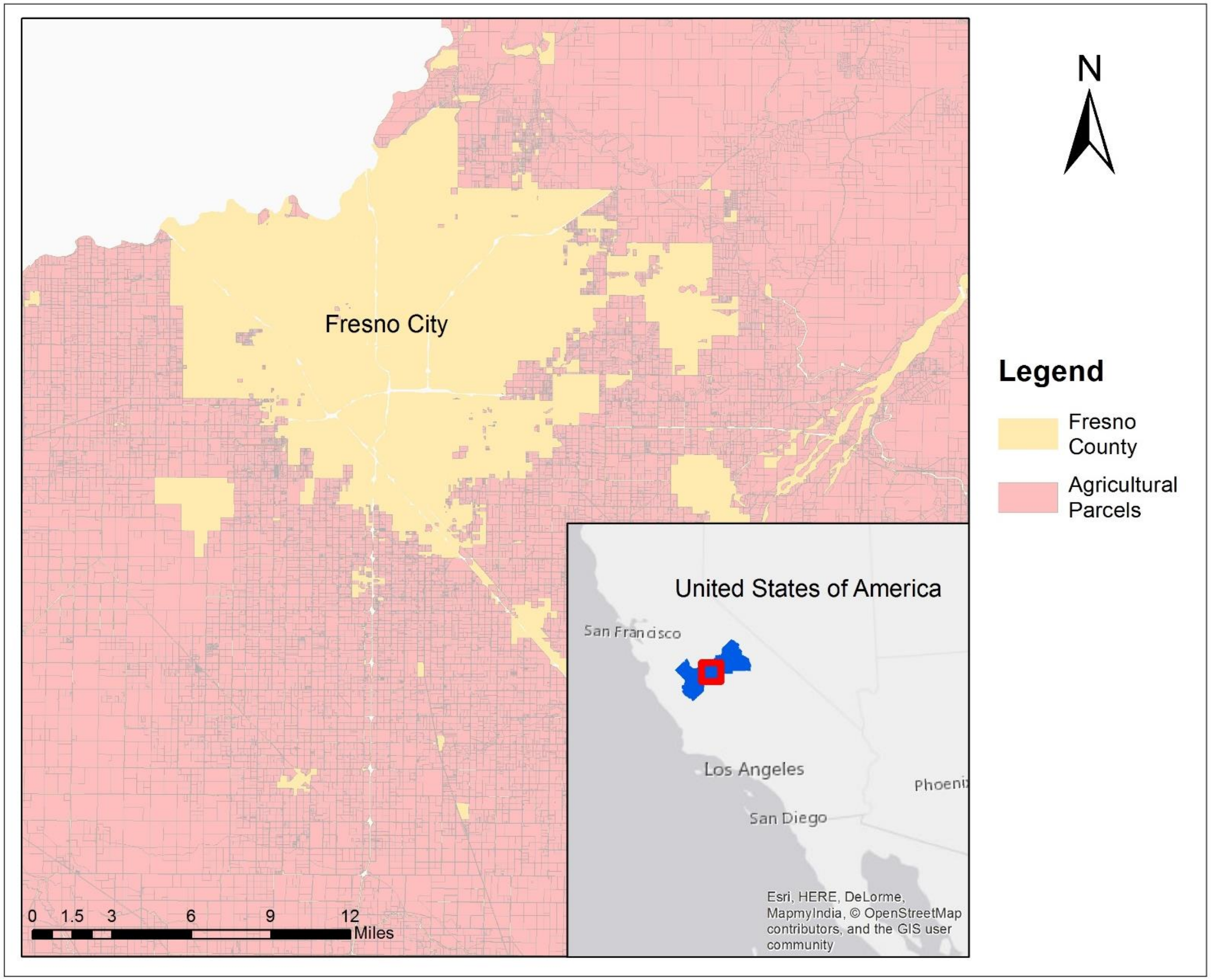

Figure 13 Agricultural parcels for pre-screening step (Fresno City area)

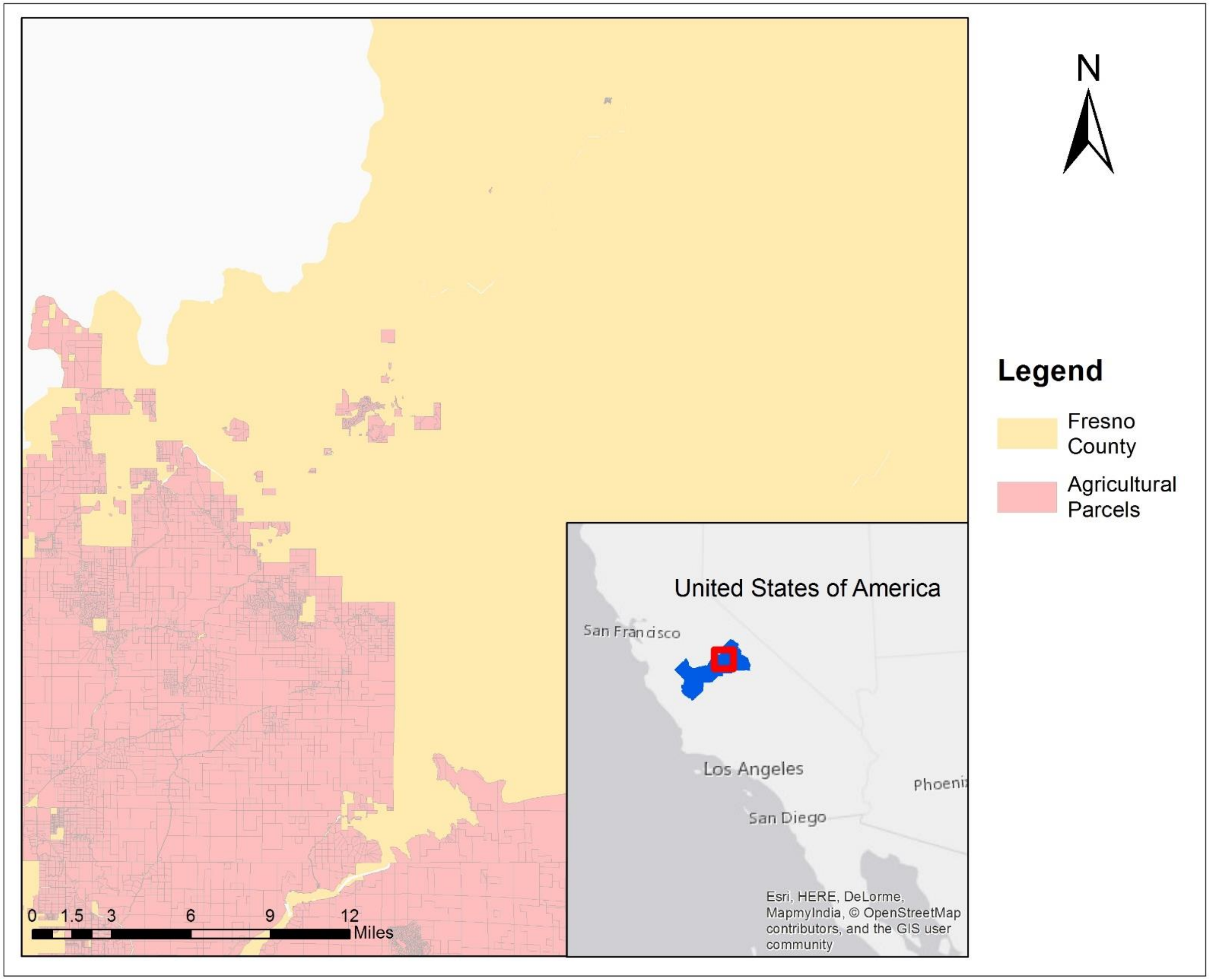

Figure 14 Agricultural parcels for pre-screening step (Northeast end of Fresno County)

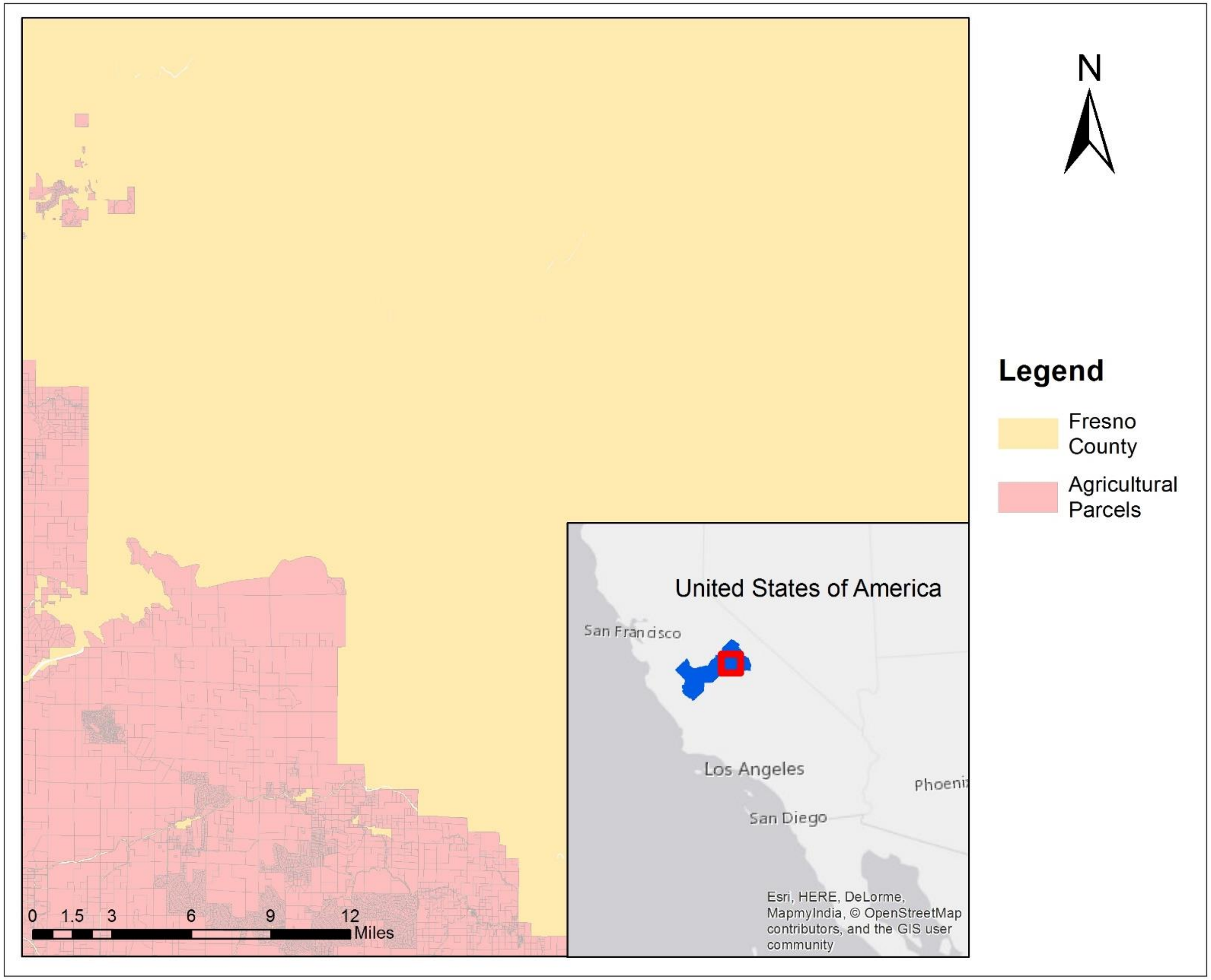

Figure 15 Agricultural parcels for pre-screening step (Southeast end of Fresno County)

From the maps illustrated above, it is evident that most of the agricultural land is concentrated towards the western end of the County, as the eastern end consists of the Sierra Nevada Mountain Range as the border, making it unideal for agricultural use as well as ground-mounted solar PV installation. Though the resulting dataset still contains a large amount of parcels, it would be useful to narrow these down further to identify the most ideal parcels based on certain characteristics.

4.1.2 Parcel Area

The next step of the pre-screening analysis was to identify parcels which met the area requirements for a small-scale solar PV plant, as defined by the NREL. Due to the benefits of a decentralized energy supply, this thesis focused on small-scale PV farm installations. This meant that only parcels with an area between 7.6-152 acres were considered for this thesis. This pre-screening step further reduced the number of viable parcels to 21,122 parcels, and produced Figure 16, pictured below.

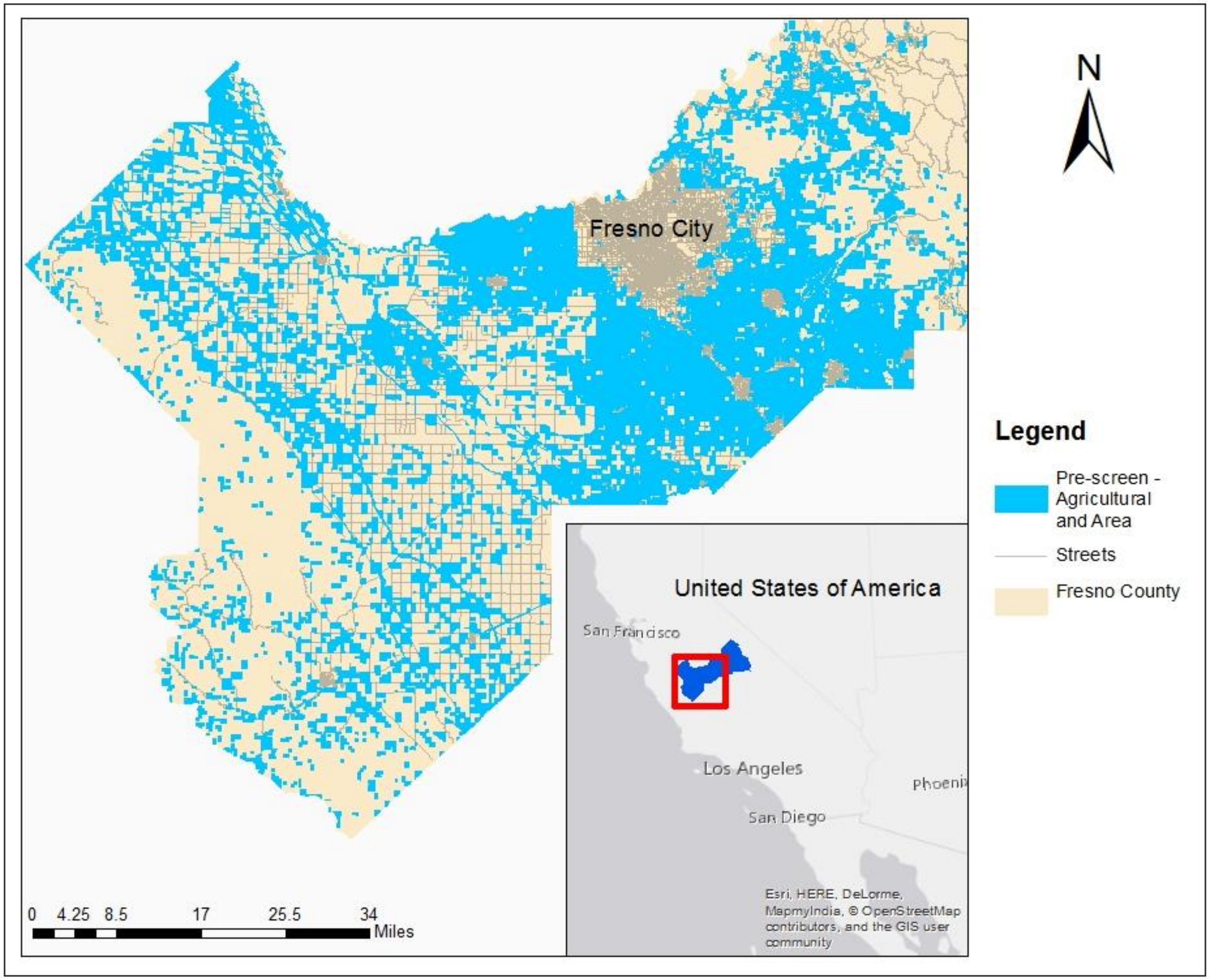

Figure 16 Only Agricultural parcels with an area of 7.6-152 acres

From this map, the density of the parcels suggests the agricultural parcels that meet the parcel area criteria seem to be more concentrated just outside of Fresno City, and scattered throughout the southern and western portions of Fresno County. Having the right parcel size is important in a solar developer's decision making; parcels too small are not able to hold capacities desired, and parcels too large may cost developers more than they need to spend.

4.1.3 California Land Conservation Act Parcels

Over the years, many Californian agricultural landowners have entered binding contracts with their local government prohibiting their land from being used for anything other than agriculture. Therefore, it is absolutely necessary to screen out parcels which are tied to a contract and cannot be developed as a solar PV farm. This pre-screening step reduced the number of viable parcels to 11,048 parcels and produced the following output, Figure 17.

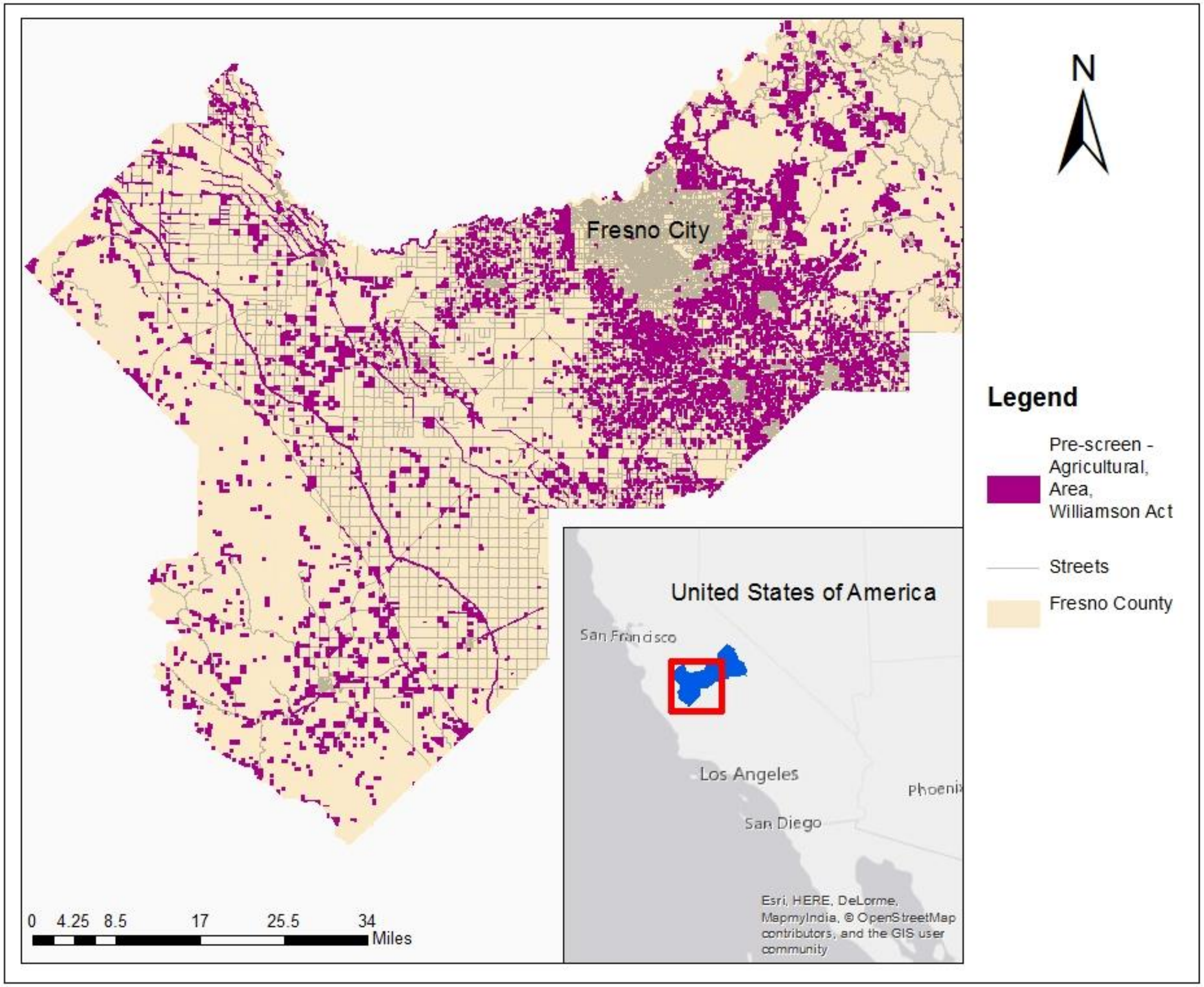

Figure 17 Fresno County agricultural parcels with an area of 7.6-152 acres and are not bound by a Williamson Act Contract

When compared to the previous output from the parcel size step, the result of this pre-screening step appears to be a sparser version of the parcels identified in the previous output. Similar to the parcel size map, viable parcels appear to be concentrated just outside of Fresno City, and scattered throughout the southern and western portions of Fresno County. As a result of this pre-screening step, Figure 17 illustrates all agricultural parcels which are not bound by a Williamson Act contract, and can be subject for other compatible uses.

4.1.4 Transmission Lines

Transmission lines are another important factor to consider. Due to the high costs and difficulty of constructing electricity transmission infrastructure, it is ideal for developers to screen out parcels that are too far away from transmission lines. Therefore, this thesis identified parcels within 0.5 mile of a transmission line to be suitable for PV farm development. This pre-screening step reduced the number of viable parcels to 6,412 parcels, and produced the following output, Figure 18:

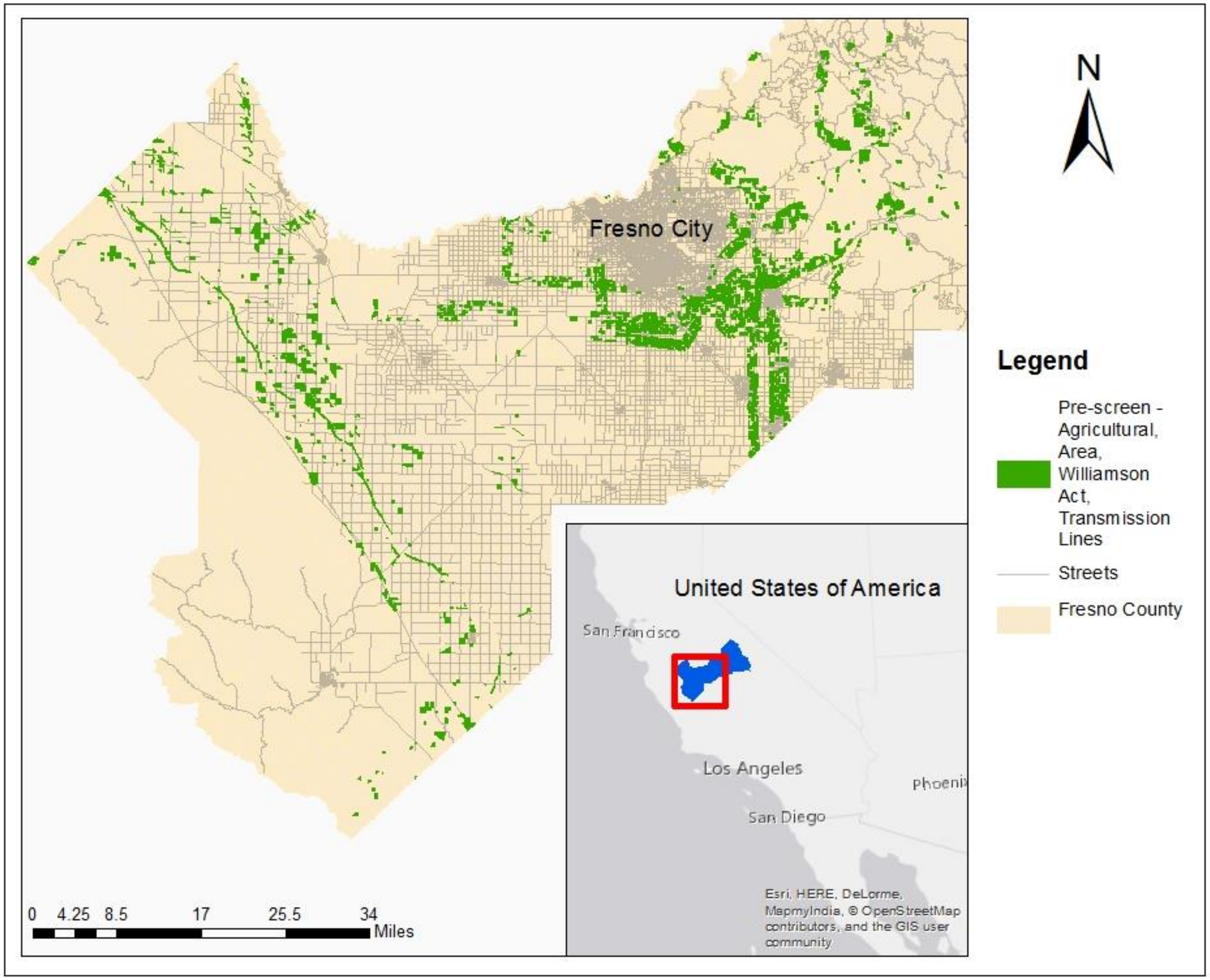

Figure 18 Agricultural parcels with an area of 7.6-152 acres, not bound by a Williamson Act Contract, and within 1/2 mile of a transmission line

Of all the pre-screening steps, the most obvious pattern emerges from this one. As a culmination of all the pre-screening steps, this one reduced all the remaining parcels even further, to illustrate only those parcels that were within ½ mile of a transmission line. The resulting output indicates that most of the ideal parcels remain concentrated around Fresno City, presumably where much electricity transmission infrastructure resides due to the presence of a metropolitan area. Scattered parcels are also apparent along the route of the transmission lines throughout the southern and western portions as well as the areas just east of Fresno City.

4.2 Outcomes from Raster Analysis

4.2.1 Solar Analyst

Sites that passed the pre-screening analysis make up the possible suitable sites for this site, with a total of 6,412 potentially parcels. The DEM data was clipped by the final output of the pre-screening analysis. This clipped raster showing elevations only for those parcels that have fallen within all the pre-screening steps were analyzed. This clipped raster was inputted into Esri's Area Solar Radiation function. The output resulted in a raster illustrating the level of solar insolation on each parcel, illustrated below in Figures 19 and 20.

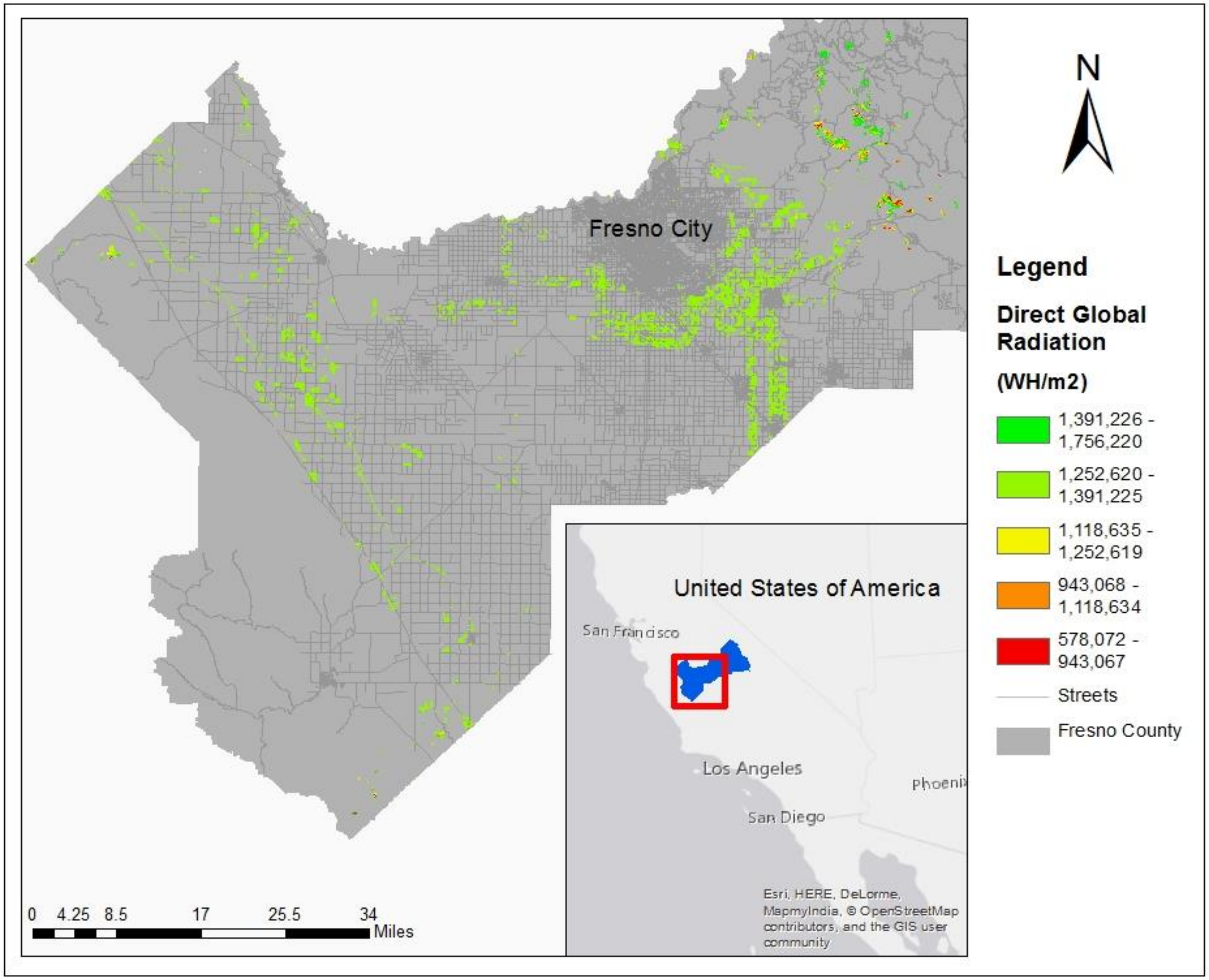

Figure 19 Direct Global Radiation values for pre-screened parcels

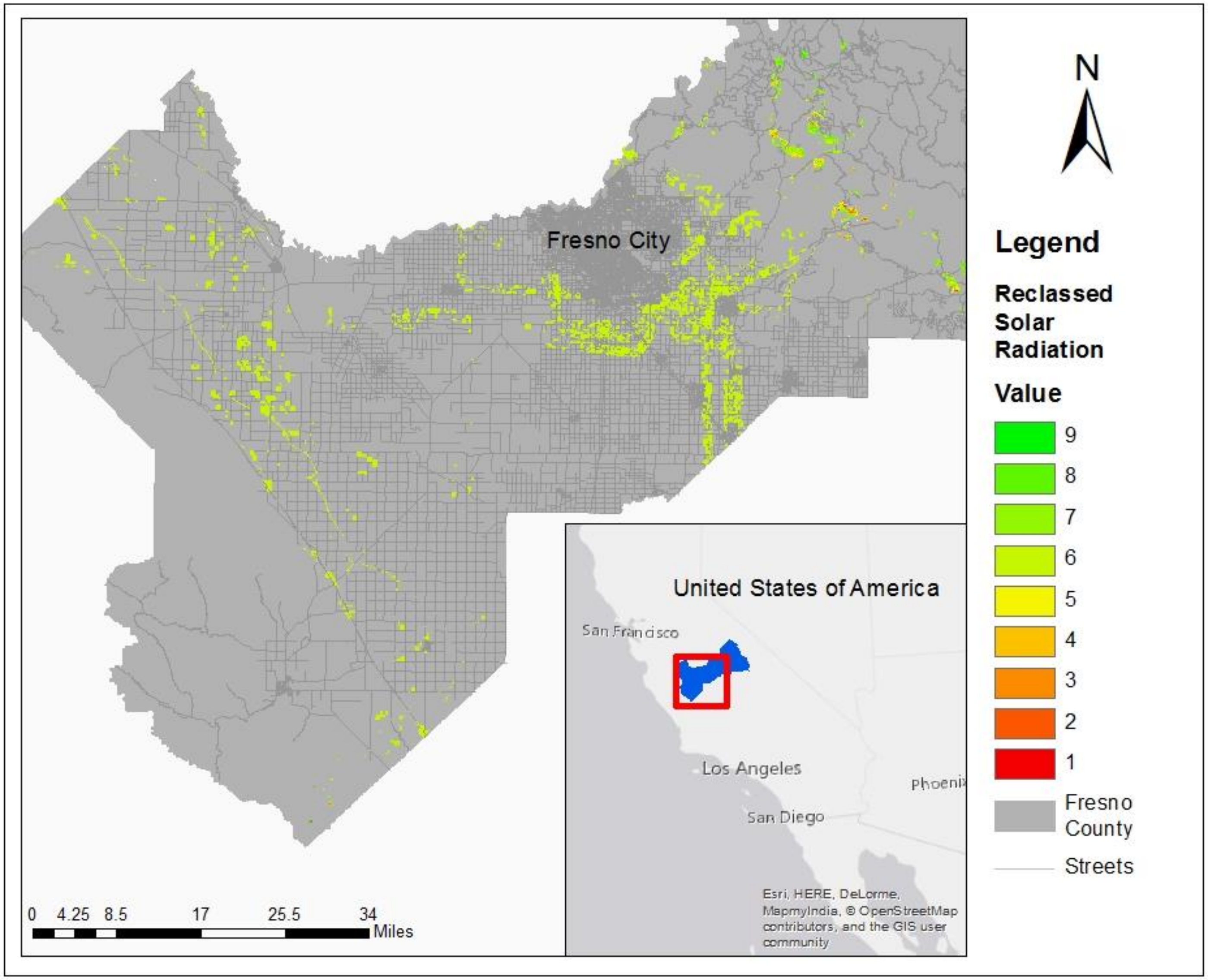

Figure 20 Reclassified Direct Global Radiation values for pre-screened parcels

Overall, most of these parcels were relatively high in incoming solar radiation values, with a few exceptions of patches with significantly lower radiation values in the east, towards the mountains. Due to the relatively high values across the board with a few exceptions, an equal interval distribution was used to break these values into 9 classes for the reclassification step, to be used in the Weighted Sums scoring step. Furthermore, having higher solar values meant more potential electricity generation from a parcel. This meant that the direct global radiation was a particularly important characteristic for a parcel, from the developer's perspective. Thus, this was given a stronger weight of 1.5 in the Weighted Sums analysis.

4.2.2 Slope

The slope of a parcel is also particularly important from the PV farm developer's point of view. Regrading land can incur additional costs in the development phase as well as maintenance phase of a solar plant. Thus, it is ideal to identify and illustrate parcels with relatively flatter land surfaces than others, as well as exclude any parcels with parcels outside the ideal slope range for a solar PV farm. For this thesis, a 3% rise was the maximum slope for any parcel to be considered for this step. All the parcels that had less than a 3% rise were scored based on 9 classes. For this step, the clipped DEM raster was inputted into Esri's Slope function. The output resulted in a raster illustrating slope for these parcels, illustrated below in Figures 21 and 22:

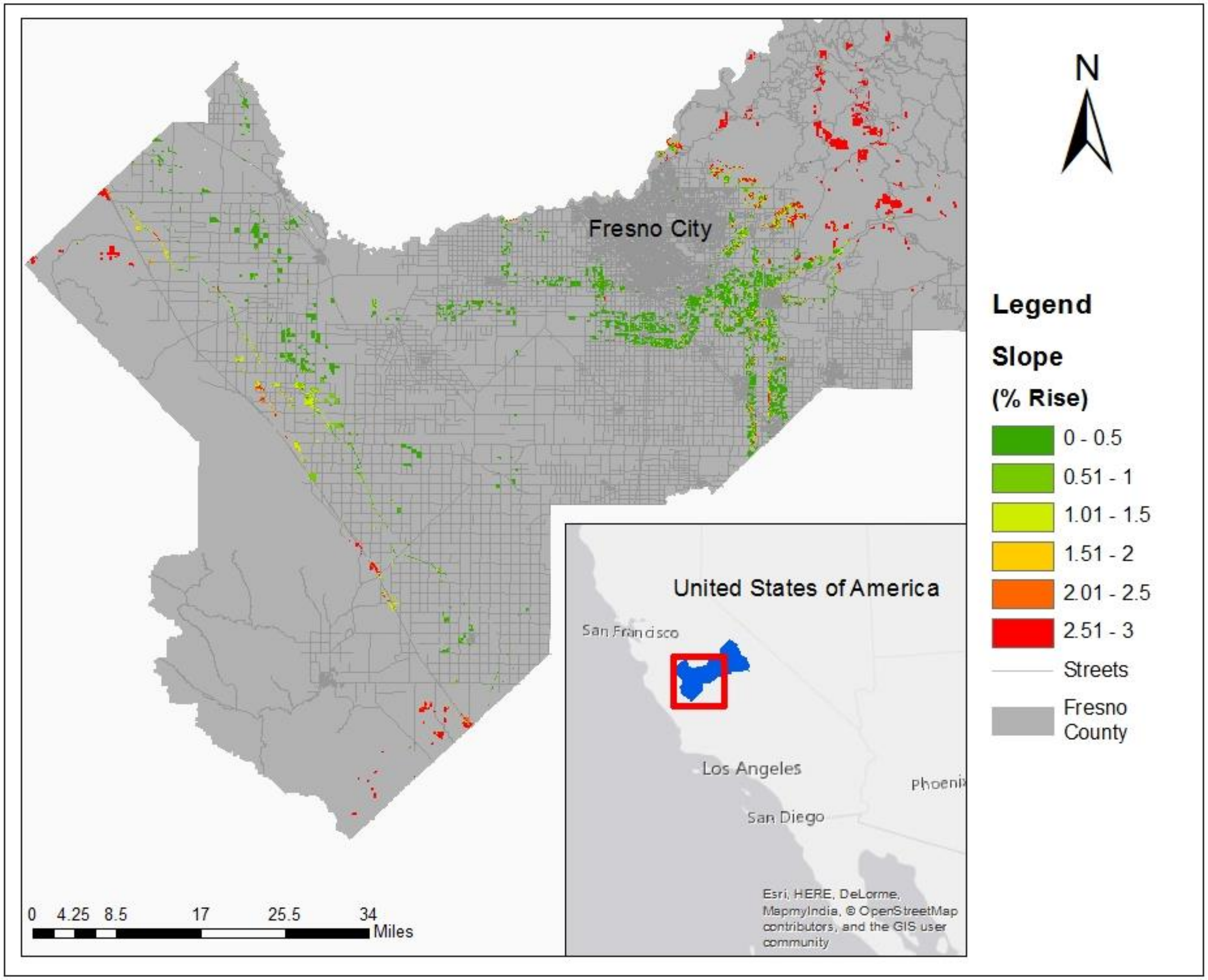

Figure 21 Slope for pre-screened parcels

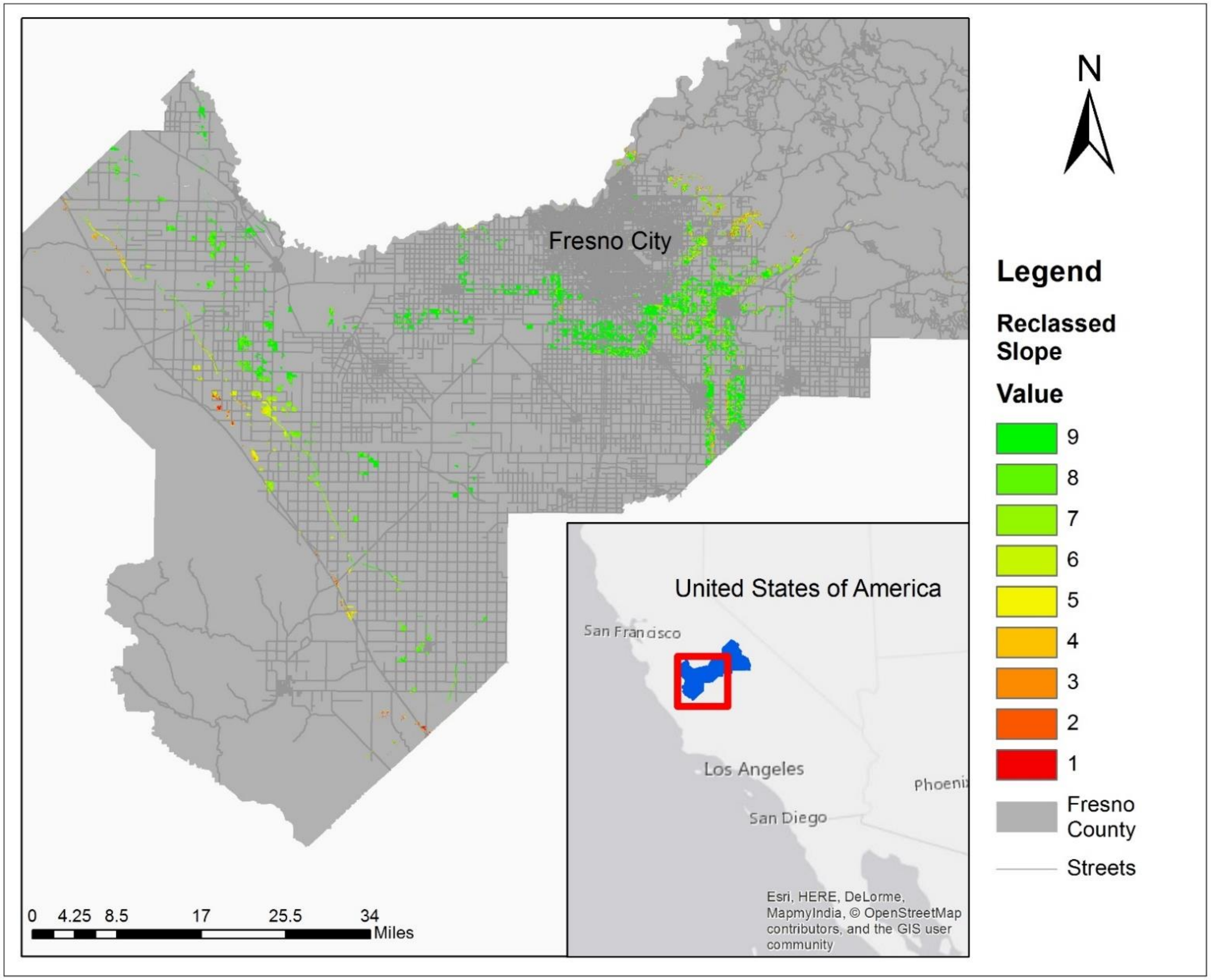

Figure 22 Reclassified Slope for pre-screened parcels

From this map, it is evident that the eastern parcels, closer to the Sierra Nevada mountain range generally had significantly steeper slopes than those closer to Fresno City, as well as the parcels further to the south and west of Fresno County. Though regrading a parcel's slope can be costly, it is a factor that we can control, unlike direct solar radiation. Thus, this was given a lower weight of 1 in the Weighted Sums analysis.

4.2.3 Distance from Streets

The distance a parcel lies from a street is also an important factor in PV farm development. Roads provide access for the construction, maintenance, as well as decommissioning of a PV plant. The further a parcel is from a road, the higher the cost will be to create and maintain a road that provides access to the parcel, even if it is just a dirt road. Thus, illustrating the distance of a parcel to the nearest road would be particularly useful to solar PV farm developers. This raster analysis step resulted in the distance raster illustrated in Figure 23, which was clipped by the pre-screening layer to produce Figures 24 and 25 below.

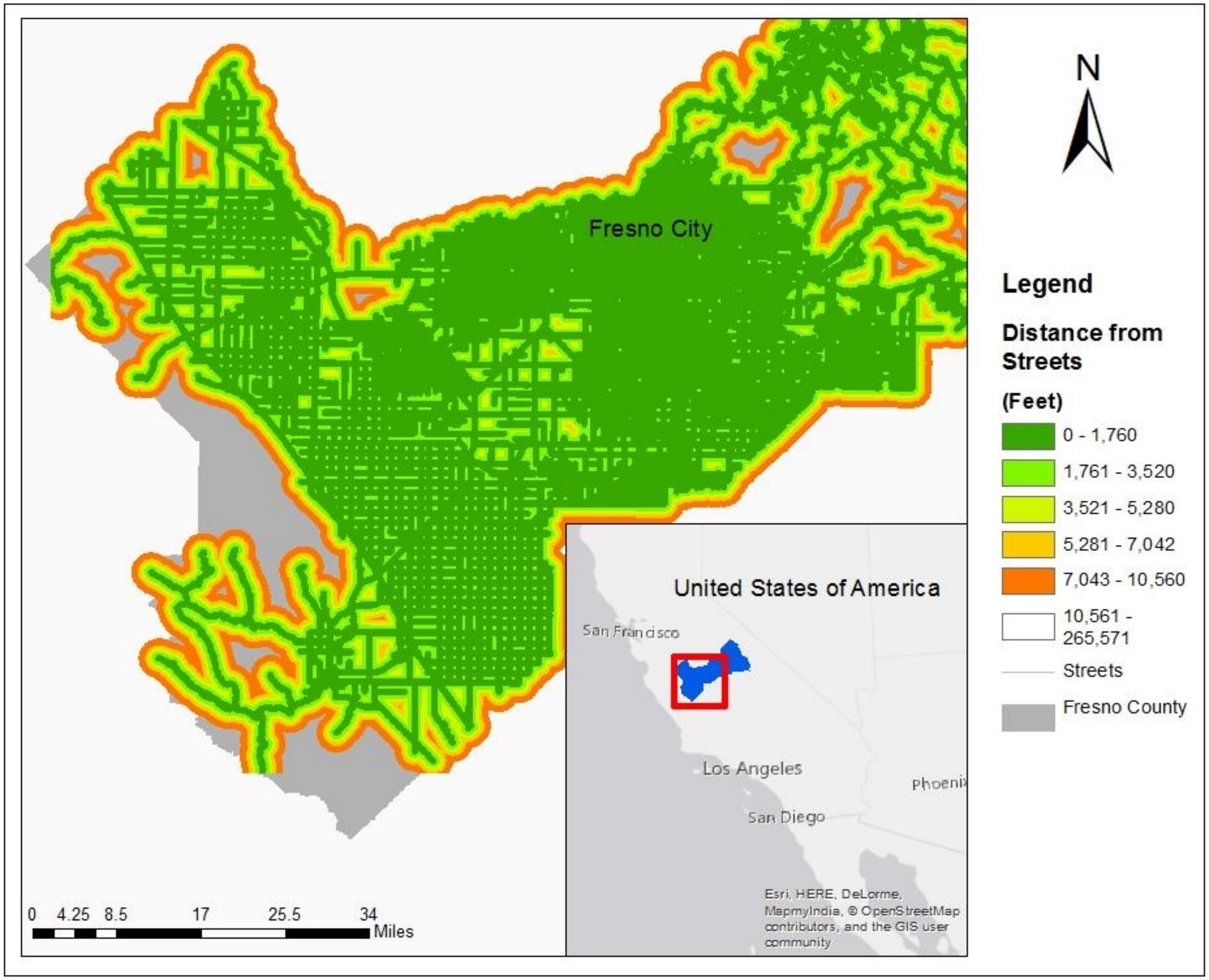

Figure 23 Distance raster for streets

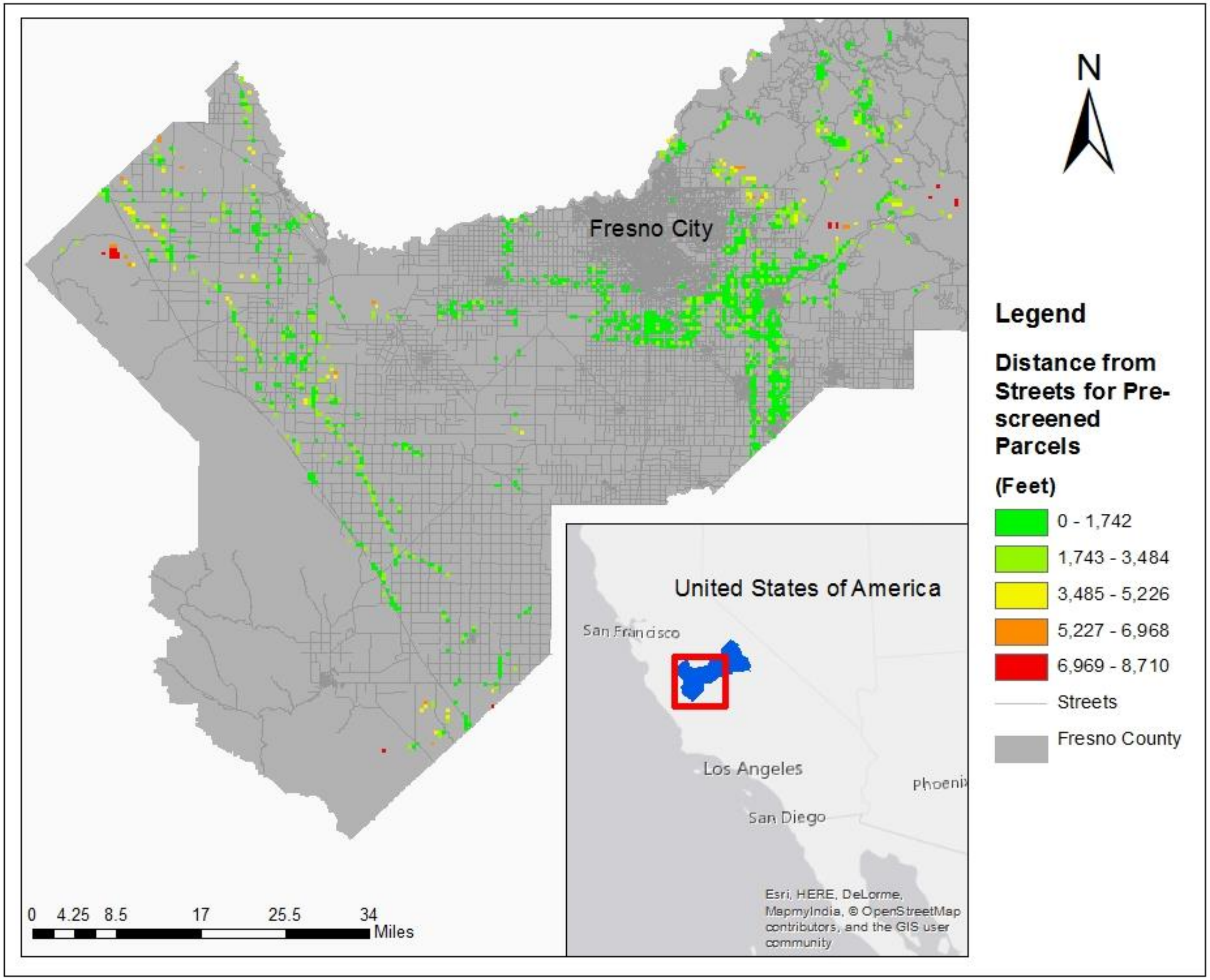

Figure 24 Distance from streets for pre-screened parcels

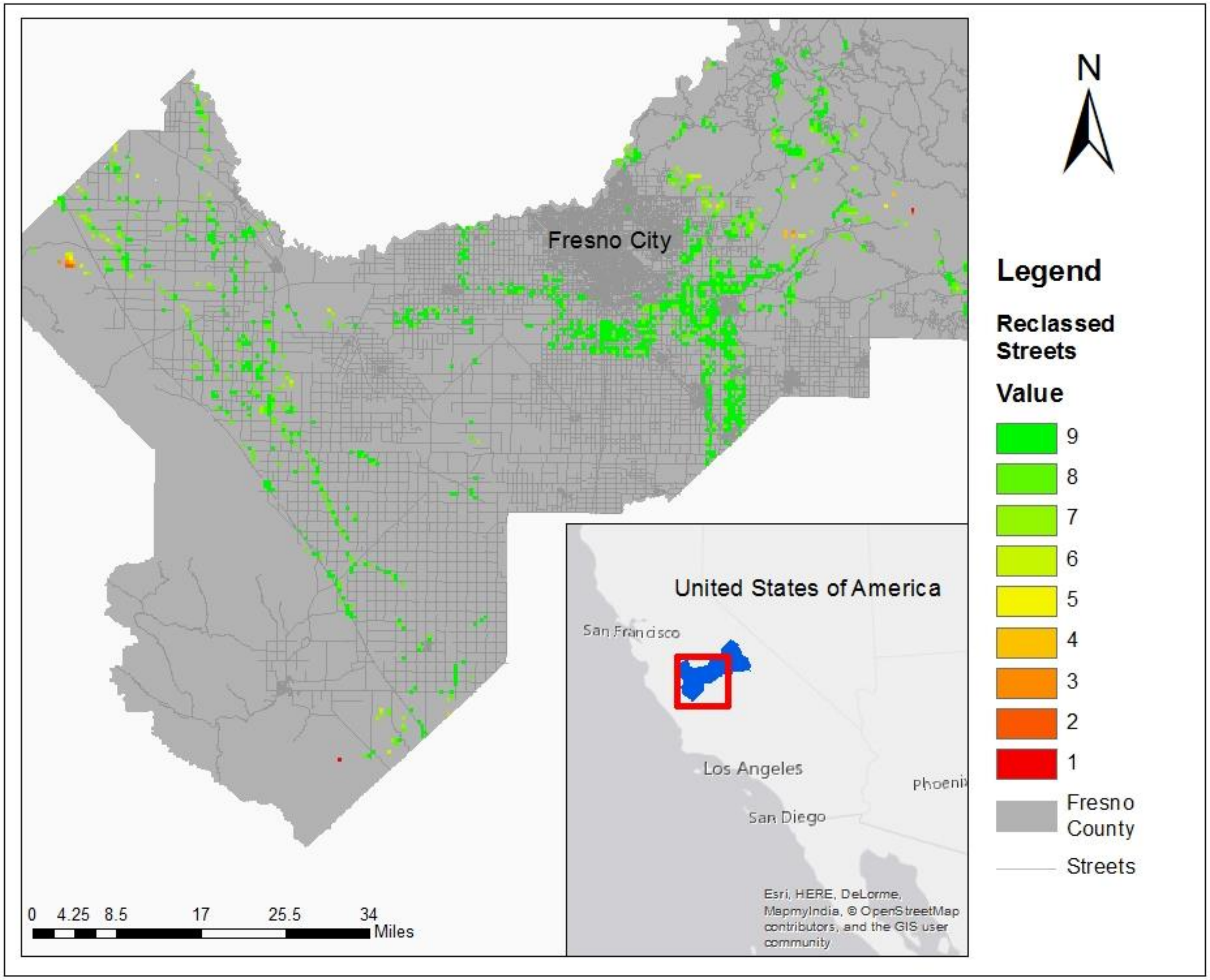

Figure 25 Reclassified Distance to Streets for pre-screened parcels

From this map, it is clear most these parcels lie within a 1,742 feet of a street, making them ideal parcels, in terms of distance to streets. There are a few exceptions which lie a little further from streets, to the far west and south of Fresno County, as well as just to the east of Fresno City. However, even these lie within 1-mile of a street. Though distance to roads are still important from the developer's point of view, it is easier and cheaper to lay out a dirt path than it is to regrade an entire parcel. Thus, for the Weighted Sums step of this thesis, the distance to roads layer was given a weight of 0.5.

4.2.4 Weighted Sums

In order to give a general understanding of the most ideal parcels for development in Fresno County, the three raster datasets needed to be aggregated and quantified into meaningful data that can be easily understood. To do this, the Weighted Sums tool was used to multiply all the raster layers together and assigning a total score to the three datasets, as one raster. The amount of incoming radiation, deemed the most important of the three rasters, was given the highest weight of 1.5, followed by the slope (1.0), which beat out the distance to roads (0.5) due to relative difficulty and cost of each factor would add to a potential development. The Weighted Sums tool produced the following output, scoring parcels on a scale of 12 to 22.5, with 12 being the lowest score and 22.5 being the highest. All parcels where there was "No Data" for any of the three rasters were removed from the data. The final output is illustrated below in Figure 26:

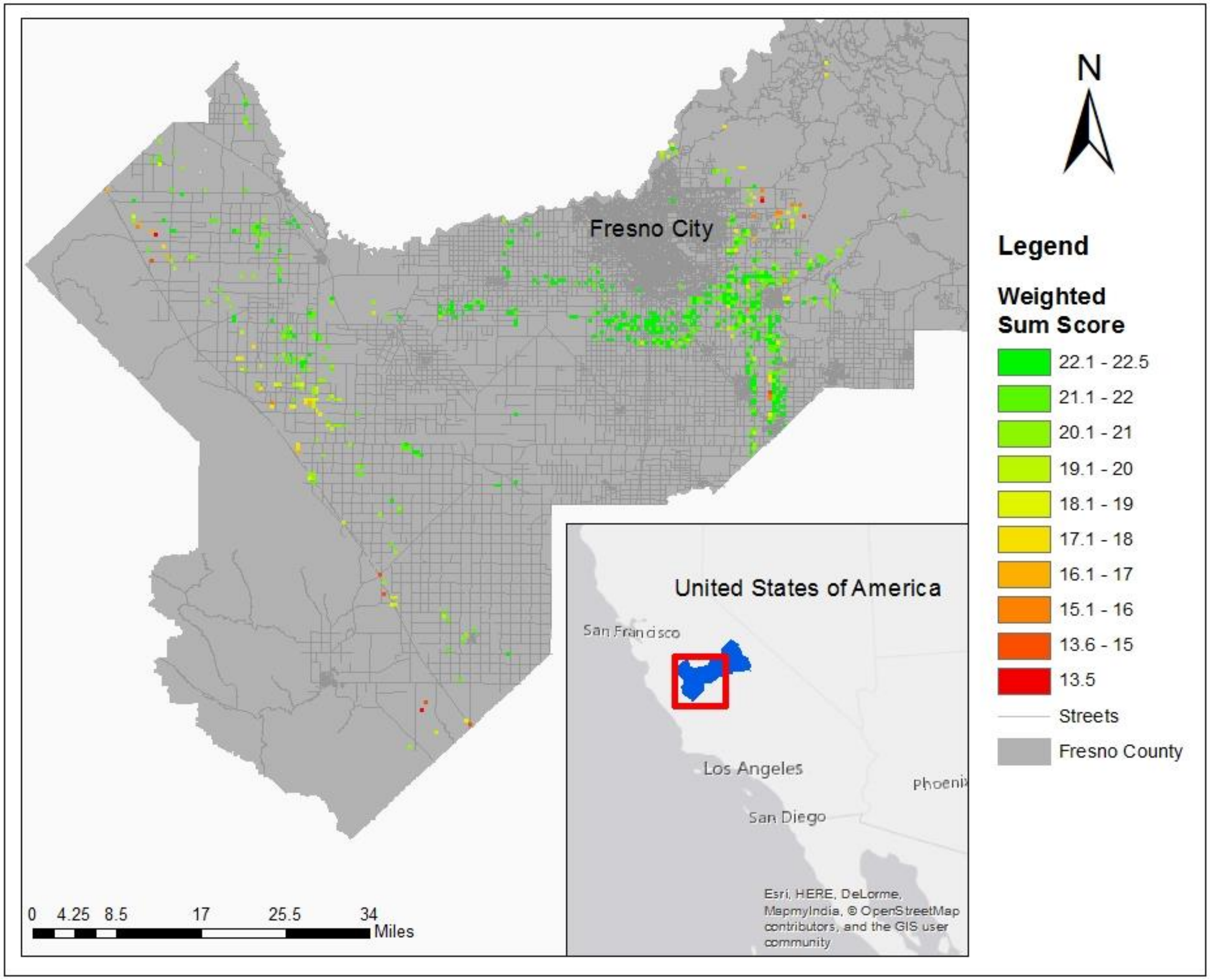

Figure 26 Weighted Sums output

The data that did not meet the criteria for any of the three raster analyses were omitted from this output. The result is a much sparser dataset. This map illustrates all the parcels scored based on how well they met each of the three raster criteria, relative to each other. The highest scoring parcels were relatively concentrated towards the south of Fresno County. Most parcels which lie in the mountain ranges to the east were removed at this stage.

By comparing the four outputs in the raster analysis portion of this thesis, we can study why certain parcels scored poorly or better than each other. As an example, in the western portion of Fresno County, the scattered parcels mostly scored high, with a few exceptions towards the far west. Upon examining the three rasters from the raster analysis portion, it is evident that these low scores can be attributed to the steeper slopes as well as further distance to streets for these parcels. Further analyses are conducted in the following chapter of this thesis.

Chapter 5 Discussion

The resulting raster datasets showed promising results with regard to identifying suitable sites for small-scale fixed-axis solar PV farm development. These datasets considered multiple variables for pre-screening, and illustrated the level of suitability for each of the variables, along with one final amalgamation of the three layers into a weighted sums output. Though more than half of the samples achieved relatively high scores, this chapter focuses on further discussion into the distribution of these high scoring parcels, as well as any outliers.

5.1 Key Observations

Overall, it is key to note that general pattern of the ideal parcels tend to follow the path of the transmission lines. These parcels are scattered in a ring just outside the City of Fresno, and follow along the transmission lines. The main trend observed was that the far eastern and western portions of Fresno County scored generally low, due to the mountainous terrain. There were absolutely no suitable parcels further to the east, due to the mountainous terrain and distance from infrastructure. Generally, parcels that scored well in the final Weighted Sums analysis scored well in all three categories of the raster analysis. The lower scoring parcels usually scored poorly in both slope and distance to streets categories, but still scored relatively high in the incoming solar radiation category; this shows that lack of human infrastructure is actually what is prohibiting most of these lands from being ideal for solar development.

The results of this thesis indicate that parcels that meet all the minimum requirements were mainly concentrated just outside of Fresno City, in a ring towards the south of Fresno City. Ideal parcels were also scattered throughout the western portions of Fresno County, in the flat valley area between two mountain ranges to the east and the west. Upon closer examination of these areas in the four resulting layers from the raster analysis of this thesis, it is evident that these areas scored relatively high in all three raster categories, producing a high score in the final weighted sums output. The slope raster indicates that these parcels generally possessed relatively level slopes of between 0-0.5% rise. Further, these parcels also resided well within the ideal distance to a street of 1 mile. Finally, these parcels average incoming solar radiation, when compared to the actual range of the values for the entire clipped sample.

Most of the parcels further to the east, where the Sierra Nevada Mountain range exists, were eliminated due to high slope values or distance from streets. The remaining few parcels that were analyzed in the Weighted Sums output all achieved relatively low scores in the Weighted Sum approach, except for one parcel, located at the far east of the where the sampled parcels exist. Upon closer examination of this parcel on the four final raster outputs, it is apparent that this parcel scored well when it came to distance from streets and slope, but did not score well when it came to the solar radiation values. This suggests that some other environmental factor such as surrounding topography was affecting the parcel such that it was not receiving ample solar radiation.

To the immediate east of Fresno City lies a small cluster of parcels, which scored relatively low (13.5-17 points, with the highest possible being 22.5). Again, comparing the all four of the raster output maps, it is evident that these parcels scored relatively low in terms of slope, and average in terms of distance to streets and solar radiation.

Parcels in the far west portion of Fresno County received relatively high scores as well, but seemed to score lower as we move further west. While the high scoring parcels are evidently scored well in all three variables, the low scoring parcels appeared to have lower scores in the slope variable, due to its proximity to the more mountainous terrain to the west.

To the far south of Fresno County are a few parcels which scored high, along with a few parcels that scored relatively low. These parcels are on the periphery of Fresno County, and presumptuously further away from the heart of civilization. These wide-open types of land, away from the heart of civilization are quite ideal for solar farms and are of particular interest to this thesis. There is a smaller chance of future buildings going up around the parcel that could obstruct incoming solar radiation. It is further away from the "backyard" of most people, and would not be a displeasure to as many drivers passing through the areas due to less traffic in these more peripheral areas of Fresno. This has the potential to make the permitting process for the parcel easier due to fewer objections to the new project, and lower overall impact on the surroundings.

5.2 Significance of Observations

The methodology of this thesis took an entire county, which included close to 300,000 parcels, and narrowed them down to a few thousand parcels illustrated in a meaningful fashion to visualize potentially suitable parcels based on multiple variables for small-scale fixed axis solar PV farms. Now that these parcels have been visualized on a map, developers, government decision makers and future researchers can take a closer look into these high scoring parcels and single out parcels which may be particularly suitable for their purposes. Ultimately, the resulting outputs give a rough idea of where suitable parcels for small-scale solar PV development are concentrated, and serves as a starting point for developers and government decision makers to begin their search for suitable parcels.

According to the NREL, PV systems generally require a minimum solar radiation of 3.5 kWh/m^2/day to be economically viable, but can be offset by state and utility incentives (EPA and NREL 2013, 20). This translates into about 1,277,500 WH/m^2/yr, a level where most parcels met. All the parcels that went through the solar raster analysis portion of this thesis had enough average incoming radiation to meet this criteria, except for those in the lowest tier, which also scored poorly in the final Weighted Sums analysis.

Though there are many high-scoring parcels just outside of the Fresno City area, it is important to keep looking further away from the city, to the more wide-open primarily agricultural-focused lands close to the periphery of Fresno County. These parcels would create relatively low impact in terms of the population affected, and would not generate as much traffic in busy areas during construction phase. Furthermore, these plants would look more similar to their surroundings, attracting less attention to the change in landscape, which is often a concern when constructing new solar photovoltaic plants. These ideal parcels would include those to the far west as well as the far south, which scored well in all three raster variables.

It is also important to note that these parcels are relatively close to a major interstate freeway, the I-5, which can be used to efficiently transport materials and equipment to and from the site during construction. Though being close to a major freeway has its benefits, it also has its costs. Proximity to a major freeway means there would be more dust resulting from the constant traffic on the freeway. This means that after development, solar panels may need to be washed more often, to ensure maximum energy efficiency out of the solar panels, adding to maintenance costs.

In a similar study by Janke (2010), Janke also used a multi-criteria approach in his GIS analysis to model solar farms in Colorado, which also considered seven criteria like this thesis. Though Janke had a more land cover-based selection criteria, the results were similar to the observations in this thesis; the ideal parcels were scattered mostly just outside the city, but relatively close to infrastructure such as roads and transmission lines.

A histogram of the final output, illustrated below in Figure 27, shows that close to half of the final parcels landed a maximum score (22.5), while relatively fewer scored poorly. It seems there is a promising amount of land in Fresno County for solar PV farm development. The poor scoring parcels were primarily concentrated to the far west and east portions of Fresno County, closer to the steeper mountain ranges. These low scores were primarily attributed to the steeper slopes of the areas, and occasionally attributed to the incoming solar radiation and distance to streets. Comparing the four raster outputs from this thesis can provide much insight into why these parcels scored low and high, which can really help developers or government decision makers single out suitable parcels for their own needs.

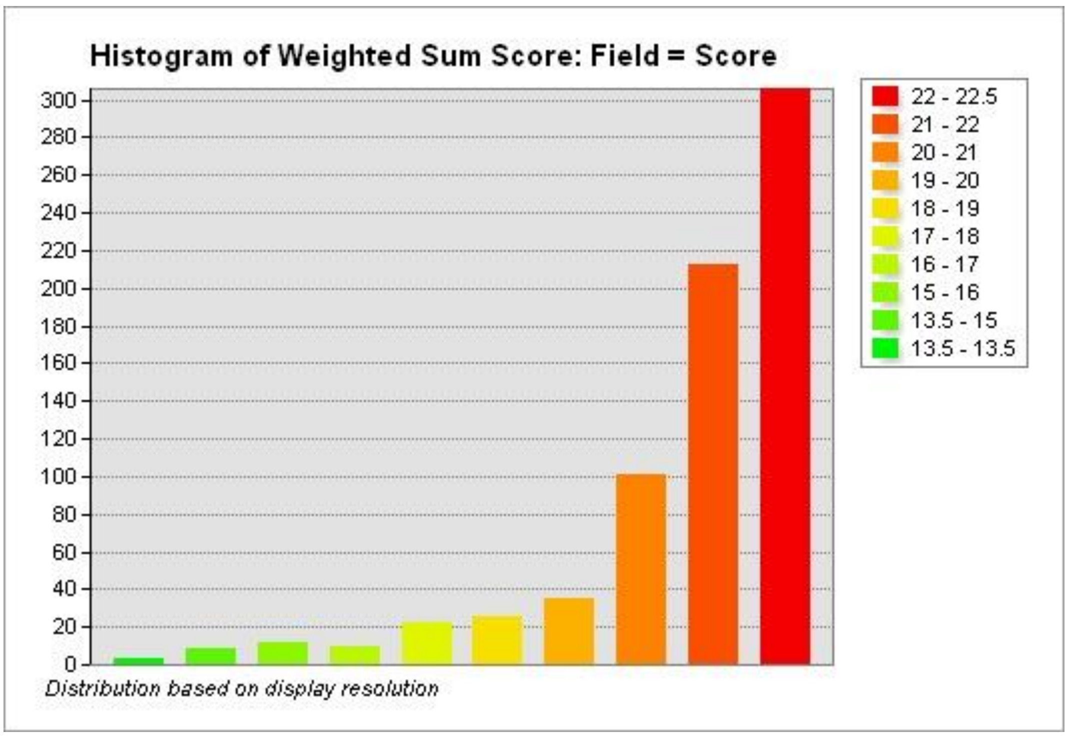

Figure 27 Histogram of Weighted Sums output

When compared to studies to a similar previous study by Yassine Charabi and Adel Gastli (2011), this thesis can be viewed as an enhancement on the study conducted in 2011. In their PV site suitability analysis, Charabi and Gastli considered a total of nine factors in their suitability analysis, while this thesis considered seven. Though there are some differences, one key difference was that Charabi and Gastli were unable to include the transmission line data because they could not obtain it, while this thesis was able to use transmission line data in a limited way. However, both studies had similar results; parcels seemed to be more limited by lack of human infrastructure than by other factors.

Furthermore, in another PV site suitability study by Xiao, Yao, Qu and Sun (2014), the researchers considered twelve factors in their classification of suitable land. Similar to both Charabi and Gastli's (2011) study as well as this thesis, the results suggest that lack of human infrastructure limited ideal areas more than other environmental factors. However, in the 2014 study, the researchers also considered land cover and orientation, which also appear to have a relatively large effect on the suitability of a parcel. From these observations, it is important to note that land suitability for PV solar installations is rarely limited by incoming solar radiation, and more often limited by lack of human infrastructure as well as various physical characteristics of the land.

5.3 Future Work

This thesis has demonstrated the application of GIS techniques in a solar PV site suitability analysis based on multiple criteria. In the future, it can serve as a model for developers, government decision makers, and researchers alike, to study solar PV farm site suitability for their uses. Accordingly, there are several ways in which a future researcher or developer may build on this thesis in their work.

Keeping the original datasets from Fresno County and the USGS updated is important for this thesis. Each year, infrastructure changes, as well as zoning and Williamson Act contracts.

Thus, for developers, updating the data for these steps in the methodology is crucial to ensuring the accuracy of the analysis.

An idea that could bolster the utility of this thesis, is to combine the raster datasets from this thesis as well as any other future studies in to a web or mobile app, which allows the user to mouse-over or touch each parcel to reveal all the relevant characteristics of the parcel in a pop-up. This would provide the tools to compare the variables and datasets, to more efficiently single out suitable parcels for developers' or government decision makers' needs.

An interesting variable to look at would be proximity to other solar projects nearby. This would be of particular interest to developers, as it would make for an easier permitting process with a nearby neighbor to follow as a model. Even simply a layer showing existing projects in the area would provide much information to developers on where to site their developments. Not only would this help in decision making, but it would also serve as sort of a test to see whether or not the parcels indicated in study are, in fact being developed into solar farms.

Regrettably, due to lack of funds, I was unable to retrieve current up-to-date transmission line data, so I had to retrieve outdated transmission line data from a past researcher, which was not high enough resolution for the raster analysis portion of this thesis. This meant that distance to transmission lines was used in a pre-screening step, rather than part of the final raster analysis. Transmission infrastructure is often an important consideration when it comes to solar PV farm development, as getting electricity to the grid for use is the primary goal of the PV farm. However, constructing new transmission infrastructure is often costly, thus distance to transmission lines would be a very important factor that solar developers would need to look at.

Furthermore, this thesis only serves as a general representation of ideal sites for small-scale solar PV development in Fresno County; further economic as well as technical studies would be required before any developer or decision maker can make the decision to develop the land. Technical studies to learn about the feasibility and generation potential of these parcels would need to be done to illustrate the whole picture on whether or not specific parcels would be suitable for development. Economic feasibility is also another important factor that goes into the development of these PV farms. Studies on the costs of building roads and other required infrastructure depending on the specific characteristics of these parcels would also be necessary for companies and government decision makers to truly assess each sites' suitability according to their individual needs.

Finally, it would be particularly interesting to do a solar site suitability analysis for just the parcels which are bound by Williamson Act contracts. The Williamson Act contract is a binding contract between agricultural land owners and the local government restricting the land use to only agricultural uses. It would be useful for government decision makers to study these parcels for their solar resources as a reference to additional solar resources that may be available to them, but cannot be harnessed due to legislation. This could illustrate the potential of these contracted lands to generate electricity using solar PV technologies, and perhaps provide an argument for releasing some more of these parcels from the binding Williamson Act contract. On the contrary, this may also show that these lands may not have much suitability for solar PV farm developments and further establish the importance of Williamson Act Contracts. In the most ideal situation, this could identify individual parcels which are highly suitable for solar PV development, allowing for government decision makers as well as land owners to better understand whether or not the Williamson Act is benefiting their property the way they think.

References

BRE Group, “Planning guidance for the development of large scale ground mounted solar PV systems,” *BRE National Solar Centre* (October 2013).

Brown, Katie, Kosol Kiatreungwattana, Gail Mosey, Shea Jones-Johnson, Craig Dufficy, Joe Bourg, Angela Conroy, Meghan Keenan, and William Michaud, “Best practices for Siting Solar Photovoltaics on Municipal Solid Waste Landfills” *National Renewable Energy Laboratory, United States Department of Energy (February 2013).*

Carrion, J. Aran, A. Espin Estrella, F. Aznar Dols, A. Ramos Ridao, “The electricity production capacity of photovoltaic power plants and the selection of solar energy sites in Andalusia (Spain),” *Renewable Energy 33 (2008) 545:552.*

Charabi, Yassine and Adel Gastli, “PV site suitability analysis using GIS-based spatial fuzzy multi-criteria evaluation,” *Renewable Energy* 36 (March 2011): 2554-2561.

County of Fresno, “About the county,” *The Official Website of Fresno County (n.d.).*

Demirbas, A., “Global renewable energy projections,” *Energy Sources Part B* 4(2009): 212-224.

Esri. "ArcGIS Help 10.1 – Area Solar Radiation (Spatial Analyst)." ArcGIS Help 10.1. (2013). http://resources.arcgis.com

Esri. "ArcGIS Help 10.1 – Weighted Sum (Spatial Analyst)." ArcGIS Help 10.1. (2013). http://resources.arcgis.com

Fu, Pinde and Paul M. Rich, “Design and implementation of the solar analyst: an ArcView extension for modeling solar radiation at landscape scales,” In Proceedings of the Nineteenth Annual Esri User Conference, San Diego, California (1999).

Gabbard, R. Todd, “Green energy, an A-to-Z guide: photovoltaics,” *SAGE Publications* (2011) 347-354.

Gabbard, R. Todd, “Green energy, an A-to-Z guide: solar thermal systems,” *SAGE Publications* (2011) 409-412.

Gazheli, Ardjan and Luca Di Corato, “Land-use change and solar energy production: a real option approach,” *Agricultural Finance Review (March 2013).*

Goetzberger, Adolf, Christopher Hebling, and Hans-Werner Schock, “Photovoltaic materials, history, status and outlook,” *Materials Science and Engineering* 40 (January 2003) 1-46.

Green, Martin A., Keith Emery, Yoshihiro Hishikawa, Wilhelm Warta, Ewan D. Dunlop, “Solar cell efficiency tables,” *Progress in Photovoltaics*23, no. 1 (2014) 1-9.

Dubaya, Ralph and Paul M. Rich, “Topographic solar radiation models for GIS,” *International Journal of Geographical Information Systems* 9, no. 4 (1995): 405-419.

Janke, Jason R., “Multicriteria GIS modeling of wind and solar farms in Colorado,” *Renewable Energy* 35 (April 2010): 2228-2234.

Johansson, Thomas B., Anand Patwardhan, Nebojsa Nakicenovic, and Luis Gomez-Echeverri, “Global energy assessment toward a sustainable future: key findings summary for policymakers technical summary,” *Global Energy Assessment* (2012).

Lehman, Ronald, “Concentrated solar thermal facilities: a GIS approach for land planning,” *University of Southern California (May 2011).*

Macknick, Jordan, Brenda Beatty, and Graham Hill, “Overview of opportunities for co-location of solar energy technologies and vegetation,” *National Renewable Energy Laboratory, United States Department of Energy (December 2013).*

McGreevy, P., “Gov. Brown signs law requiring 33% of energy be renewable by 2020,” *Los Angeles Time* (April 2013).

Munsell, Devon, “Closed landfills to solar energy power plants: estimating the solar potential of closed landfills in California,” *University of Southern California (May 2013)*.

Ong, Sean, Clinton Campell, Paul Denhold, Robert Margolis, and Garvin Heath, “Land-use requirements for solar power plants in the United States,” *National Renewable Energy Laboratory, United States Department of Energy (June 2013).*

Panwar, N.L., S.C. Kaushik, and Surendra Kothari, “Role of renewable energy sources in environmental protection: a review,” *Renewable and Sustainable Energy Reviews* 15 (2011): 1513-1524.

United States. Environmental Protection Agency and National Renewable Energy Laboratory. Best Practices for Siting Solar Photovoltaics on Municipal Solid Waste Landfills. February 2013.

United States. Energy Information Administration. State Electricity Profiles 2010. January 2012. http://www.eia.gov.

Xiao, Jianhua, Zhengyi Yao, Jianjun Qu, and Jiahuan Sun, “Research on an optimal site selection model for desert photovoltaic power plants based on analytic hierarchy process and geographic information system,” *Journal of Renewable and Sustainable Energy 5,* 023132-1 (2013)

Zweibel, Ken, James Mason, and Vasilis Fthenakis. "A Solar Grand Plan." Scientific American 298, no. 1 (January 01, 2008): 64 - 73. http://people.bu.edu