COFFEE QUALITY ZONATION IN THE

MONTECILLOS MOUNTAIN RANGE, HONDURAS

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this Research Paper.

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ABSTRACT

Coffee originated in Ethiopia, probably in the Province of "Kaffa" and was spread to Asia, Europe and the Americas in the 17th century. Two main species are cultivated today: *Coffea arabica* and *Coffea canephora.*This study focused on the coffee cup quality of Arabica coffee, which was measured through sensorial analysis of fragrance, body, acidity, taste, and aftertaste to provide a final grade. A dataset consisting of a total of 83 observations from the Montecillos mountain range in Honduras was analyzed using three ordinary kriging models. Cross-validation results demonstrated that the Gaussian model generated the best coffee attribute estimates. Six interpolated surfaces were produced and they all showed a common coffee quality distribution pattern. The best coffees were predicted in the central and southernmost parts of the study area. Good quality coffees were found mainly in the south. Lower quality coffees were located at lower elevations in the northern Montecillos.

ACKNOWLEDGEMENTS

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ASPE	Average Standard Prediction Error
DO	Designation of Origin
ESRI	Environmental Systems Research Institute
GIS	Geographic Information Systems
GPS	Global Positioning Systems
IDW	Inverse Distance Weighted
MPE	Mean Prediction Error
MSPE	Mean Standardized Prediction Error
PA	Precision Agriculture
RBF	Radial Basis Function
RMSPE	Root Mean Square Prediction Error
RVT	Regionalized Variable Theory
SRMSPE	Standardized Root Mean Square Prediction Error

Chapter 1: Introduction

1.1 Spatial Analysis and Geographic Information Systems in Agriculture

Agriculture is a field that fits very well with the application of Geographic Information Systems (GIS). Since they are natural resource based, almost all agriculture field data have a spatial component (Pierce and Clay, 2007). This spatial component can be outlined with the application of spatial analysis techniques and GIS tools.

Today, due to the availability of precise GIS tools such as sub-metre Global Positioning Systems (GPS), high resolution remote sensing data and robust GIS software, it is possible to differentiate and quantify in great detail soil types, yield, and soil nutrient content within small agricultural areas (Sonka et al., 1997). The use of these new technologies in agriculture is known as Precision Agriculture (PA) or precision farming.

Precision agriculture aims to identify, analyse, and manage in-field variability. PA contributes to reducing environmental impact and increases profit by applying inputs at an appropriate rate only where they are needed (Alberta Agriculture and Rural Development, 2007). Examples of the application of precision agriculture in coffee are: a) the use of unmanned aircraft to collect images from Hawaiian coffee plantations in order to predict the best harvest time (NASA, 2002) and b) coffee quality analysis by using correlation in Minas Gerais, Brazil (Queiroz et al., 2007).

In Central America, there are many other coffee projects that have used geo-referenced data to publish coffee farm information, such as the Cup of Excellence, an annual event

where the best coffees are selected and auctioned to the highest bidder. Although spatial analysis in agriculture is not yet as developed as in other disciplines, it has showed great potential to identify spatial variability in agricultural areas (Pierce and Clay, 2007). The application of spatial analysis and GIS provides new ways to support the decision making process in the food industry.

1.2 Study Area

The Republic of Honduras covers 112,498 km^2 and is located in the middle of Central America (Figure 1.1). Honduras has a large Caribbean Sea coastline in the north and a shorter coastline to the south along the Pacific Ocean; in the east, it shares a border with Nicaragua; and to the west, it borders Guatemala and El Salvador. Honduras is the most mountainous country in Central America and it is in these mountains where most of the coffee grows. The tropical temperatures and rainforest microclimates found in Honduras create a suitable environment to produce good quality coffees.

The Montecillos mountain range is located in the central western part of Honduras (Figure 1.2). Coffee is the most important crop in this region and coffee farms can be found from 400 to 1800 m above sea level. Montecillos is well recognized in international markets for its high quality coffees. Honduras exports around 3.8 million bags (46kg/bag) every year. Forty-five percent of the national coffee production comes from the western regions in which Montecillos is located. Coffee represents 14% of the gross domestic product and is one of the most important crops in the country (Honduran Coffee Institute, 2006).
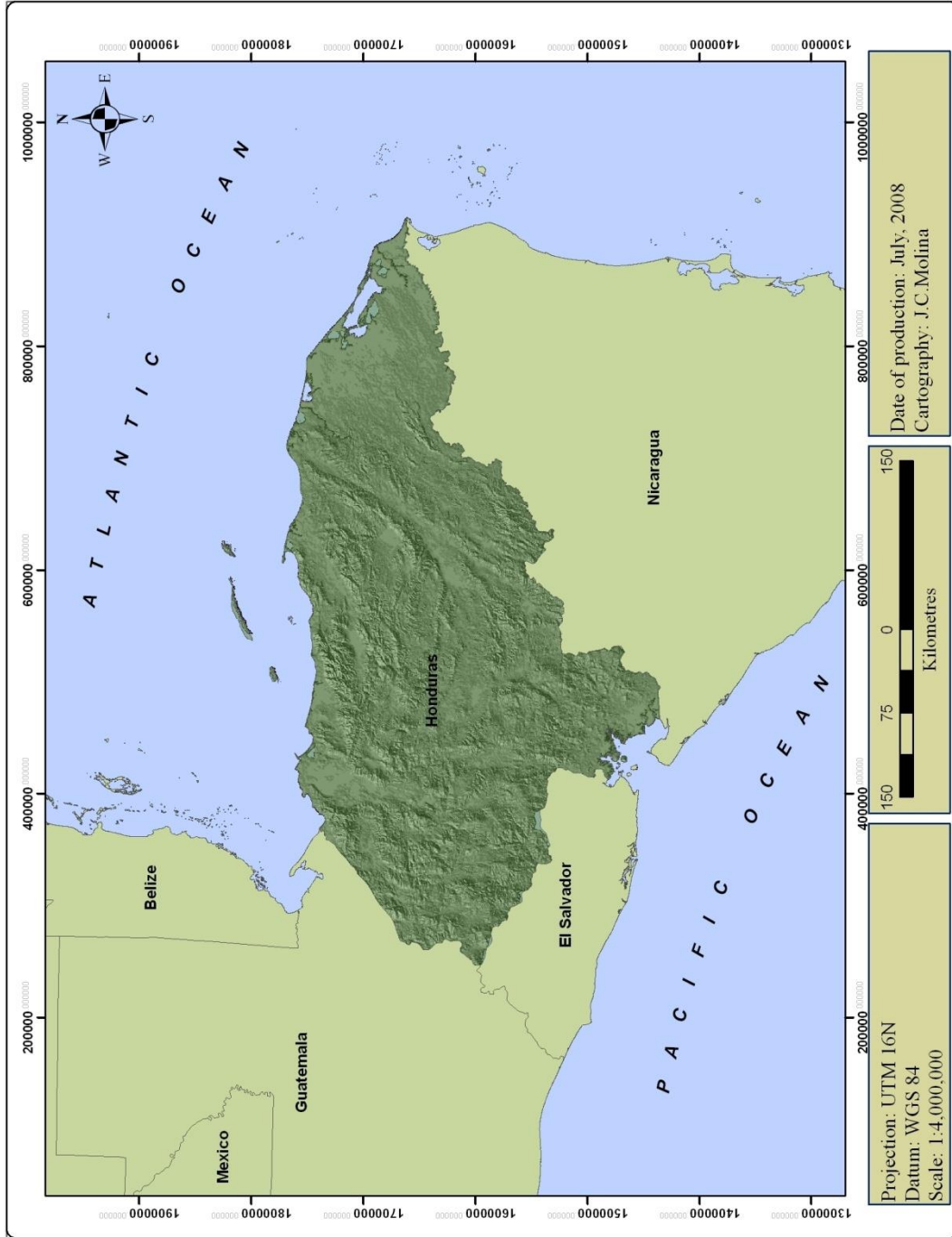
Figure 1.1. Study area, Montecillos coffee region
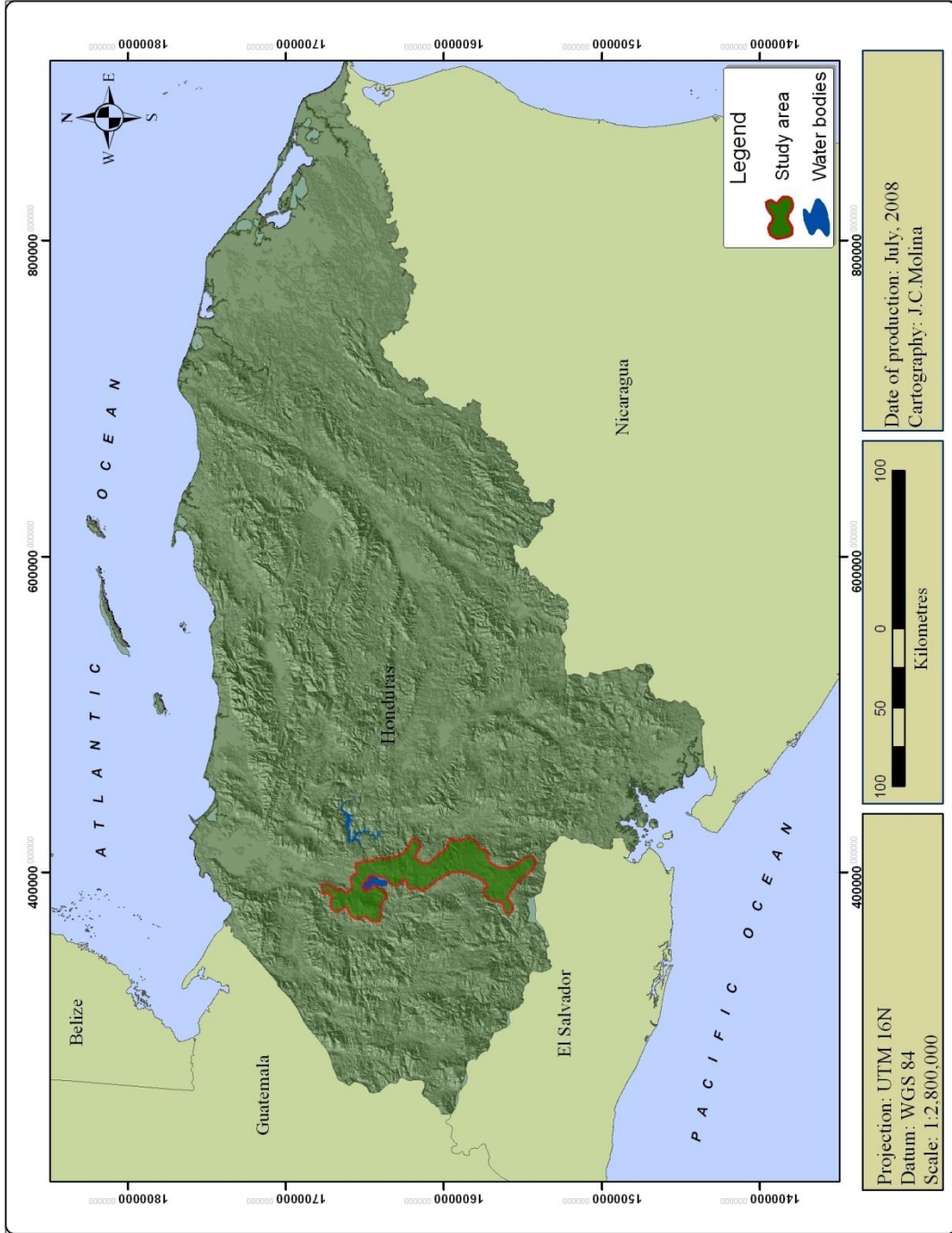
Figure 1.2. Study area, Montecillos coffee region

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In 2006, the first Central American coffee Designation of Origin (DO) was registered in this region, under the name of "Designation of Origin Marcala" which extends from the centre to the south of the Montecillos range. The main objective of the DO is to serve as a tool that allows farmers to compete with other well recognized origins such as Blue Mountain coffee from Jamaica and Kona coffee in Hawaii. Only registered farmers that comply with all the regulations of the DO will be able to label their coffee with the Marcala designation of origin, preventing low quality coffees or coffees from other sources to use the DO name (Honduran Coffee Institute, 2006).

1.3 Problem Statement

The Montecillos mountain range is one of the major coffee producer regions in Honduras. In addition, it is well known for producing one of the finest coffees of the country (Honduran Coffee Institute, 2006). However, this area has no site specific information about the different types of coffees they produce. Currently, many small and medium scale farmers sell their coffee to middle men who mix high, medium, and low quality coffees into one coffee lot. This practice is damaging the Honduran coffee image in international markets (Honduran Coffee Institute, 2006).

Having areal coffee quality information would give the local farmers a great competitive tool in order to take advantage of their microclimates, optimize international aid projects and programs, and support their marketing strategy, especially the one related to the Marcala Designation of Origin.

1.4 Research Objectives

Honduras cannot compete with top coffee producing countries such as Brazil and Colombia based on quantity, but it can from a quality perspective. Each coffee producing area has distinctive quality characteristics and identifying their distribution will provide valuable knowledge to support the decision making process of many Honduran coffee institutions. In order to generate this information, the following objectives have been set: To compare three ordinary kriging models and select the model that produces the best predictions for each of the six coffee quality attributes under study. To identify zones that may produce similar types of coffees and locate areas that are most likely to produce specialty coffees.

Chapter 2: Literature Review

2.1 History of coffee

Coffee was initially discovered growing wild on the plateaus of Ethiopia. Some researchers believe that coffee originated in the Province of "Kaffa" (International Coffee Organization, 2006). The Turkish word *kaveh* gave origin to the word coffee in English as well as café in French and Spanish. Coffee was traditionally used by nomadic mountain warriors of the Galla tribes in Ethiopia. It was first used as a food somewhere between the years 575 and 850, long before it was used to prepare hot beverages beginning around 1000 to 1300. Other tribes of northeast Africa reputedly used coffee beans as porridge or drank a wine fermented from its fruit. It is also reported that coffee beans were crushed into balls of animal fat and used as a source of energy during long journeys. The fat in combination with the high protein content (not present in the drink) of the coffee fruit was an early type of energy bar (Luttinger and Dicum, 2006).

Early consumers valued coffee as a medicament more than a recreational drink. It was often used as a remedy for a long list of maladies, especially those related to the stomach. Although coffee cultivation is reported back to 575, written reports about coffee did not appear until the tenth century. Philosopher and physician Avicenna of Bukhara (980 – 1037) referred to a drink called *bunchum* which many believe to be coffee. Avicenna wrote, "It fortifies the members, it cleans the skin, and dries up the humidities that are under it, and gives an excellent smell to all the body" (Luttinger and Dicum, 2006).

Since Islamic law prohibits the use of alcohol, coffee became an increasingly popular substitute in Islamic countries, particularly Turkey. During the 16th century, the majority of coffee was exported from the present day ports of Mocha, Yemen and Jidda, Saudi Arabia. The first coffee houses appeared in the mid-sixteenth century in Constantinople, Cairo and Mecca and were called "*kaveh kanes*". Such establishments became centres for playing games, discussing news, singing and dancing (International Coffee Organization, 2006).

Despite its growing popularity, coffee remained a monopoly of the Arab countries. No foreigners were allowed to go into coffee plantations and in order to destroy their germinating potential, coffee beans were boiled or heated before being exported. However, in the early seventeenth century, a pilgrim from India took out the first germinable seeds from Mecca to Mysore. Not long after, Dutch spies succeeded in smuggling out coffee plants that were later cultivated in their Java colonies (Luttinger and Dicum, 2006), specifically in what is now Indonesia, currently the world's fourth largest coffee exporter (International Coffee Organization, 2006).

Venetian traders were the first to introduce coffee to Europe in the early seventeenth century. In Italy, coffee was sold with other drinks by lemonade vendors. The first coffee houses appeared in Europe by the mid-seventeenth century. Later coffee houses evolved as early prototypes for the first social clubs and other social institutions. The Royal Society of Britain is believed to have begun in 1655 as a regular gathering of students originally called the Oxford coffee club. Lloyd's of London also evolved from a coffee

house, one that catered to seafarers and merchants. Attendants at this insurance firm are still called "waiters" as they were called three centuries ago in Edward Lloyd's coffee house (Intelligentsia, 2004).

The first reference to coffee in North America is from 1668 and soon after, coffee houses appeared in New York, Philadelphia, Boston, and other towns. The Boston Tea Party of 1773 was planned in the "Green Dragon" coffee house. Both, the New York Stock Exchange and the Bank of New York started in coffeehouses, in what is today the financial district of Wall Street (International Coffee Organization, 2006). Currently, coffee is the second most traded commodity in the world after petroleum. Coffee is produced in 57 countries (Figure 2.1) and Latin America is the largest exporting region in the world (Global Exchange, 2007).

2.2 Coffee, from plant to cup

Coffee is a plant that grows between the Tropic of Cancer and Tropic of Capricorn. Luttinger and Dicum (2006) suggest that in 2004, approximately 10 million hectares of coffee were planted all over the world, an area about the size of Portugal. In addition, they estimate that every cup of coffee consumed comes from an area of 0.18 square metres of land. In this day and age, to obtain a cup of coffee we use a similar procedure as our ancestors used centuries ago. This procedure consists of the following steps: 1) harvest the cherries, 2) mill and dry the beans, 3) roast and grind the beans, and 4) infuse the ground coffee.
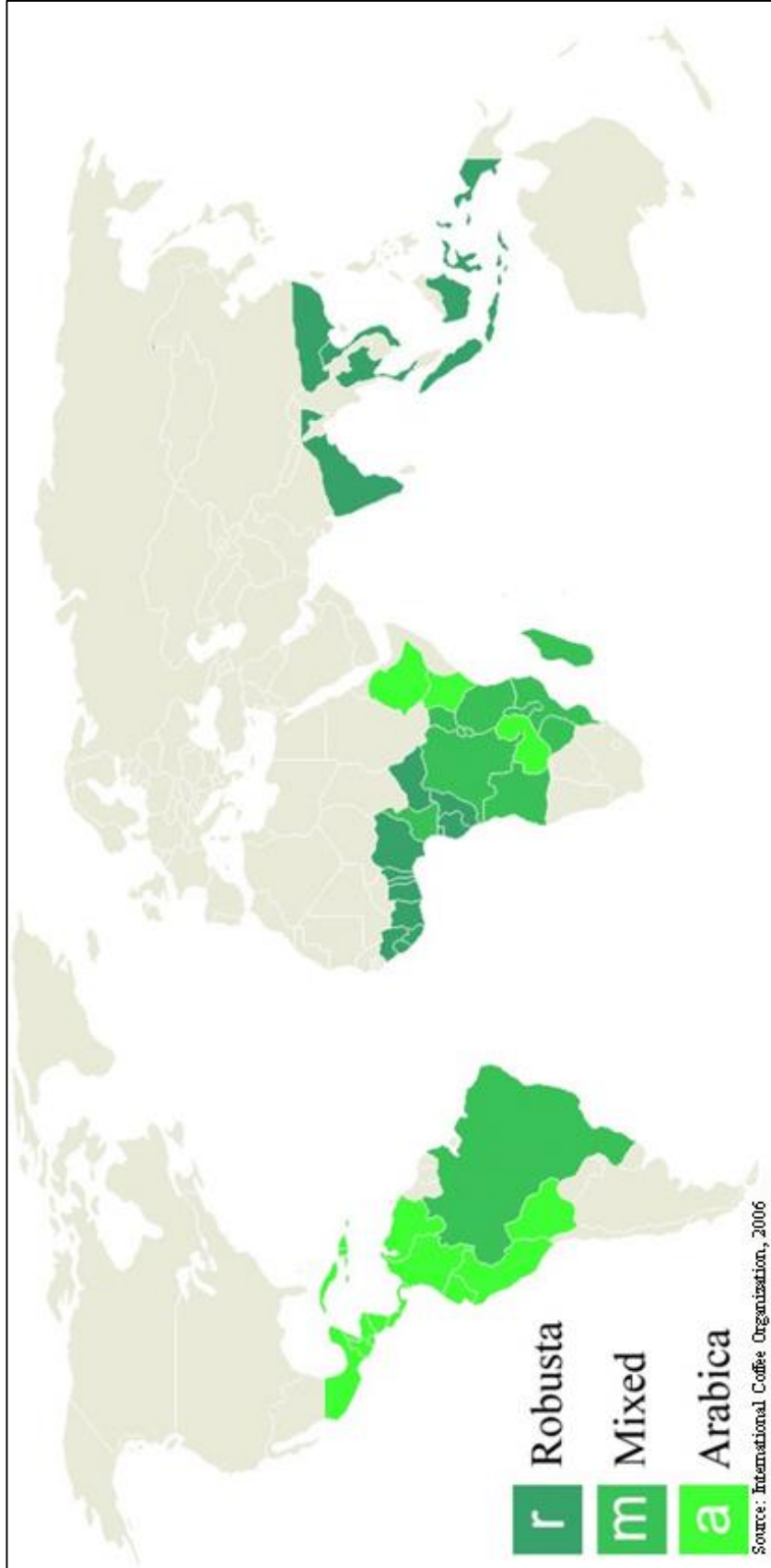
Figure 2.1. Coffee producing countries. Source: International Coffee Organization, 2006

Nevertheless, the adoption of new technologies in all the links of the coffee chain process has dramatically increased the complexity of each of these steps (Coffee Research, 2006).

2.2.1 Coffee botany and phenology

Coffee belongs to the genus *Coffea* in the family Rubiaceae. The plant is a woody shrub and in the wild grows as high as 12 metres, but for harvesting purposes is trimmed to 2 metres. Coffee grows best in tropical places from 0 to 2000 m above sea level with a lot of sunshine, moderate rainfall and pleasant temperatures (60-70°F) all year long (Luttinger and Dicum, 2006). Coffee phenology varies all over the world due to climate, species and elevation. While in Honduras the harvest period is from October to March, in Jamaica it is from August to September (Table 2.1).

Table 2.1: Coffee harvest periods

Coffee origin	Harvest period
Brazil	March-October
Colombia	Oct-Feb, Apr-Jun
Honduras	October-March
Jamaica	August-September
Guatemala	October-January

(Source: International Coffee Organization, 2006)

In flower season, groups of white aromatic flowers with abundant nectar and pollen appear. Each tree is covered with nearly 30,000 flowers that after 24-36 hours begin to develop into fruits. After pollination, flowers wither and each one is replaced by a fleshy fruit that surrounds a hard seed like a cherry (Boe, 2001) and each of these cherries contains two coffee beans. It takes about 3 years to collect the first coffee beans from a plant. Each tree produces around 2000 coffee cherries per year (4000 coffee beans) which

makes approximately one pound of roasted coffee. The coffee cherries turn from green to bright red 6 to 8 months after flowering indicating they are ready to be harvested (Luttinger and Dicum, 2006). There are more than 20 species of coffee, but only two provide the bulk of coffee consumed around the world, *Coffee arabica* known as Arabica coffee and *Coffea canephora* known as Robusta coffee.

2.2.2 The Dominant Species

Arabica and Robusta coffees differ in taste, caffeine content, disease resistance, and cultivation conditions (International Coffee Organization, 2006). Arabica coffees are the most finest and expensive coffee beans. They grow in highlands (900-1800 m) and are responsible for brewed coffee's aroma, body and smoothness. These coffee beans are the only source for specialty coffees and represent 75% of the world's coffee production. Their caffeine content (1% of the weight) is less than in Robusta (Zimmer, 2007) and is the only commercial variety cultivated in Honduras (Funez, 2006).

Robusta coffees give a more "robust" drink and are used for the lower grades of coffee sold throughout the world. In contrast with Arabicas, Robustas grow very well in lower lands and accounts for 25% of the world coffee production. Robusta is a strong variety and resists a great diversity of diseases and adverse environments, but is very vulnerable to frosts (Luttinger and Dicum, 2006). Robustas are commonly used in blends and in instant coffees. In addition, they contain about 2% caffeine by weight and are responsible for the strength and intensity of a finished cup of coffee (Zimmer, 2007).

2.3 Coffee Quality

Coffee quality is a difficult term to describe. The definition of quality has probably evolved through the centuries and depends on many factors such as soil composition, climate, pre and post harvest management, and plant genetics. Nowadays, this definition varies along the production to consumer chain (Coffee Research, 2006).

At the farmer level: coffee quality is a combination of production level, price, origin, and easiness of culture. At the exporter or importer level: coffee quality is linked to bean size, lack of defects, regularity of provisioning, tonnage available, physical characteristics, and price. At the roaster level: coffee quality depends on moisture content, stability of the characteristics, origin, price, biochemical compounds, and organoleptic quality. At the consumer level: coffee quality deals with price, taste and flavour, effects on health and alertness, geographical origin, environmental, and sociological aspects. It should be noted that each consumer market or country may define its own organoleptic qualities (organic coffee, fair trade, etc.) (Leroy et al., 2006).

This study will focus on the coffee cup quality, which is measured through sensorial analysis of coffee fragrance, acidity, body, taste, aftertaste, and final grade which is the sum of the other characteristics.

2.4 Coffee Cup Characteristics

Coffee cup characteristics are measured though the cupping process which consists of a set of procedures that through sensorial analysis appraise aroma and taste characteristics (i.e. acidity, body, aftertaste, and balance) of a coffee sample (Lingle, 1993).

Acidity is a very noticeable characteristic of good coffees from Central America, especially coffees from Montecillos (Honduran Coffee Institute, 2006). In one form, acidity can give liveliness and freshness to the coffee. In another form, it can appear as sourness. Coffee without acidity is lifeless. Coffee with too much acidity can be unpleasant (Lingle, 1993).

Body is the weight of the coffee and can best be sensed by allowing the coffee to rest on the tongue and by rubbing the tongue against the roof of the mouth. The oiliness or slipperiness of the sensation indicates the fat content. The thickness or viscosity of the sensation determines the brew's fibre and protein content (Lingle, 1993). Coffee body ranges from thin, to light, to heavy and is a result of the fat content (Coffee Research, 2006).

Coffee fragrance is responsible for all coffee flavour attributes: sweetness, saltiness, bitter, and sour tastes that are perceived by the tongue. Therefore, it might be said that coffee fragrance is the most important attribute to specialty coffee. Coffee fragrance is mainly perceived by smelling the cup of coffee (Coffee Research, 2006)

Aftertaste is the perception or taste remaining in the mouth after the coffee has been swallowed. The longer this sensation lasts the better the coffee. The flavour compounds found in the aftertaste may be associated with chocolate, tobacco smoke, a spice such as cloves, or pine sap. One or many of these taste characteristics may be present in a single cup of coffee (Lingle, 1993).

Balance measures the uniformity of the coffee taste among all the coffee cups from the same sample. If all the cups evaluated from the same sample show the same degree of intensity of fragrance, body, acidity, taste, and after taste then the coffee is awarded with a good balance (Coffee Research, 2006).

2.5 Spatial Interpolation

Interpolation is the procedure of predicting the value of attributes at unsampled sites from measurements made at specific locations within the same area or region. It is used to convert point observations to continuous surfaces. This allows the comparison of attribute spatial patterns captured by the measurements with each other. Predicting the value of an attribute at locations outside the area covered by existing observations is called extrapolation (Burrough and McDonnell, 1998).

There are many methods to interpolate data (i.e. Inverse Distance Weighted, Local Polynomial, Radial Basis Functions and Kriging.) and these methods can be divided into two groups: deterministic and geostatistical interpolators (Burrough and McDonnell, 1998). In addition, deterministic and geostatistical interpolators can be grouped into exact

and inexact interpolators. Exact interpolators predict values which are the same as the measured value at sampled locations (Inverse Distance Weighted and Radial Basis Functions). An inexact interpolator predicts values that are different from the measured values (Global and Local Polynomial) (ESRI, 2006).

Deterministic methods such as Inverse Distance Weighted (IDW) and Radial Basis Functions (RBF) create surfaces from sample points based on either the degree of similarity or the level of smoothing (ESRI, 2006). All these methods are relatively easy to perform and only require an understanding of simple statistical methods (Burrough and McDonnell, 1998). Deterministic techniques can be divided into two groups: global methods and local deterministic methods. Global methods calculate predictions using the complete dataset. Local techniques calculate predictions from the sampled points within smaller spatial areas or neighbourhoods in the study area (ESRI, 2006).

The geostatistical theory commonly referred to as kriging has its origins in the gold mines of South Africa. It was developed as a result of the need to improve prediction techniques for gold to justify the high costs of deep level mining. Kriging techniques were developed in 1951 by a geologist named Daniel Gerhardus Krige. Based on the work done by Krige, in 1970 Georges Matheron formalized the theory of regionalized variables and published the first detailed exposition on geostatistics and kriging (Houlding, 2000).

Geostatistical methods for interpolation recognize that the spatial variation of a continuous attribute is usually too unequal to be modelled by a simple smooth

mathematical function (deterministic methods). Instead, the variation can be more appropriately described by a stochastic surface (Burrough and McDonnell, 1998). Kriging is a modern geostatistical procedure that produces an estimated surface from a group of observations containing "z" values (ESRI, 2006).

In order to create prediction surfaces, kriging techniques use statistical models that integrate autocorrelation among a group of the sample points (Johnston et al., 2001). Kriging is similar to IDW in that it assigns weights to the observed values in order to estimate a value for an unknown location. However, unlike IDW, the weights assigned are based on both, the spatial correlation between the points and the distance between sampled and un-sampled points. In addition, through a cross-validation process kriging produce measures of certainty or accuracy (Johnston et al., 2001).

When data are limited, assumptions made about the variation in the samples in addition to the interpolation method chosen (and its parameters) play a critical role. Kriging is used when the variation of an attribute is irregular and the density of samples is such that simple interpolation methods may give unreliable predictions.

2.5.1 Regionalized Variable Theory

Kriging optimizes the prediction value of an attribute at unvisited points by applying Regionalized Variable Theory (RVT) which divides spatial variation into three components: 1) a structural component with a constant trend, 2) a random spatially autocorrelated component, and 3) uncorrelated noise or residual error (Burrough and

McDonnell, 1998) where the value of a random variable "Z" at a "x" location is given by the following function:

$$Z(x) = m(x) + \varepsilon'(x) + \varepsilon'' \qquad (1)$$

Where m(x) is a deterministic function illustrating the structural component of Z at (x), ε'(x) is the term representing the stochastic, locally varying but spatially dependent residuals from m(x), and $\boldsymbol{\varepsilon''}$ is a residual spatially independent Gaussian noise having the variance and the mean equal to zero (Burrough and McDonnell, 1998). In addition, kriging assumes that all random errors are second order stationary (random errors have μ=0) which presume that the covariance between any two points depends only on two factors: a) the distance and b) the direction. Their actual location is not considered into this assumption (Johnston et al., 2001).

2.5.2 Ordinary Kriging

Geostatistical methods offer great flexibility for interpolating surfaces. Within all the kriging models, ordinary kriging is the most flexible because it assumes that the mean (μ) is an unknown constant. Therefore, the random errors at the data locations are not known (Johnston et al., 2001). Ordinary kriging characterizes spatial correlation through the use of a semi-variogram model, which provides a measure of variance of differences as a function of distance between the observation points (Merwade et al., 2006). In addition, ordinary kriging is the most appropriate model for datasets that have a spatial trend (Isaaks and Srivastava, 1989). Ordinary kriging assumes the following model:

$$Z(\mathbf{s}) = \mu + \varepsilon(\mathbf{s}), \qquad\qquad (2)$$

Where $Z(\mathbf{s})$ is the unknown value of the variable at a spatial location (s), μ is an unknown constant, the median, and $\varepsilon(\mathbf{s})$ is the random error (Jakubek and Forsythe, 2004). Ordinary kriging is usually associated with the acronym B.L.U.E. for "best linear unbiased estimator". It is linear because the results of its estimates are weighted linear combinations of the dataset under study. It is unbiased because it tries to have the mean residual or error equal to zero and is best because it seeks to reduce the variance of the errors (Isaaks and Srivastava, 1989).

The following formula calculates the predictor:

$$Z(s_o) = \sum_{i=1}^{N} \lambda_i\, Z(s_i) \qquad\qquad (3)$$

Where $Z(s_i)$ is the measured value at location i, λ_i is an unknown weight for $Z(s_i)$, s_o are the coordinates of the prediction location and N symbolize the number of measured points used in the prediction of a value for a unknown location. When predictions are made at many locations, some will be above and some will be below the actual values. On average, the difference between the actual and predicted values should be zero (Jakubek, 2002).

2.5.3 Empirical Semivariogram

The empirical semivariogram is a way to identify spatial autocorrelation and look for outliers within the dataset. Each point in the semivariogram represents the difference squared between the distances of two locations. When working with larger datasets the number of pair locations will considerably increase and may become hard to manage. Due to this, ArcMap uses a technique called binning, in which locations are grouped based on specified distances (Johnston et al., 2001).

In order to create an empirical semivariogram the following steps are followed.

    a) Find all pairs of measurements

    b) Calculate for all pairs the squared difference between the values (i,j). To calculate the distance between two locations the following formula is used

$$d_{ij}=\sqrt{(x_i-x_j)^2+(y_i-y_j)^2} \tag{4}$$

    c) Group vectors or lag into bins (similar distance and direction classes)

    d) Average the square difference for each bin (in this step we take into account the assumption of stationarity).

2.6 Use of Kriging in Coffee Research

In comparison with other crops like corn where much research using geostatistics has been published (Shanahan et al., 2004), coffee has a limited number of research papers available that have utilized interpolation techniques such as kriging in order to predict agronomic variables like coffee quality. Most of the research using kriging in coffee has

been oriented to optimize the control of diseases and pests such as those published by Bedimo et al. (2007) and Musoli et al. (2007).

The limited number of publications using geostatistical interpolation methods for coffee may be due a combination of several factors such as: 1) limited funds from national governments or coffee institutions in order to invest in research 2) the large reduction in coffee prices from 2000 to 2003 (Figure 2.2) which stimulated the production of specialty coffees around the world and 3) limited access in producing countries to relatively new hardware and software tools to perform geostatistical analysis.
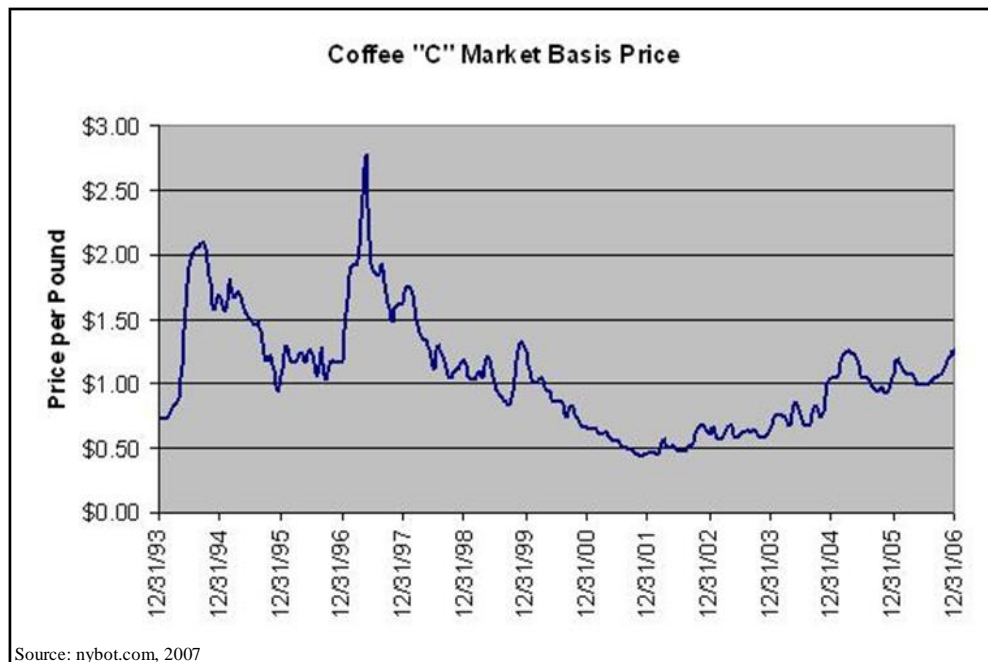
Figure 2.2: World coffee price from 1993 to 2006. Source: nybot.com, 2007

Chapter 3: Data and Methods

In order to predict the coffee quality at unknown locations in the Montecillos mountain range, the geostatistical method ordinary kriging was selected among the interpolation methods available. The kriging analysis and map plotting were performed using ArcGIS 9.2 software from the Environmental Systems Research Institute (ESRI). Software tools such as Microsoft Excel and SPSS were also used to generate statistics, graphs, and tables.

3.1 Data Collection

Data for this study were obtained from the Honduran Coffee Institute and consist of a set of 83 geo-referenced observations taken in 2006 from the Montecillos mountain range. In addition, the boundaries and the digital elevation model of the area of interest were also provided. The coffee samples' sites were randomly selected and each coffee sample was prepared by Honduran Coffee Institute technicians (harvested, wet milled, dried, stored, roasted, ground, and cupped) following a strict methodology. Each observation contains the geographic coordinates of a coffee farm and the results of its coffee quality analysis. Coffee farms were geo-referenced using GPS Garmin76S calibrated to the WGS84, UTM zone 16N projection and coffee quality samples were appraised by a group of coffee cuppers.

3.2 Coffee Cupping

Coffee quality assessment or coffee cupping was performed by a group of five senior coffee cuppers, which through sensorial analysis evaluated the following five coffee

quality attributes: 1) fragrance, 2) body, 3) acidity, 4) taste, and 5) aftertaste. From each coffee sample, five cups were evaluated with each cup containing seven grams of ground coffee and 150 ml of hot water. To give a quality score to the coffees, each quality element is assigned a value from 1 (very low quality) to 10 (exceptional quality). To give a final score or total score (Figure 3.1), an initial value of 50 points is given to each sample. This value is subsequently summed with the five averaged scores assigned to each attribute. (Honduran Coffee Institute, 2006).

TOTAL SCORE	SPECIALTY DESCRIPTION
95–100	Exemplary
90–94	Outstanding
85–89	Excellent
80–84	Very Good
75–79	Good
70–74	Fair

Figure 3.1: The coffee scoring system. Source: Roast Magazine, 2005

Coffee final scores usually range from 70 to 95. Coffees with a final score below 80 are considered of lower quality and are usually produced in the lower part of the mountain. Scores between 80 and 85 are given to very good quality coffees. Scores above 85 and below 90 are of great quality and regularly have very pleasant and unique attributes. Coffees with a final score equal or greater than 90 are very rare and show attributes that amaze the palate of many coffee experts (Honduran Coffee Institute, 2006).

3.3 Exploratory Spatial Data Analysis

Coffee quality attributes values were explored in order to examine the distribution of the data and to identify trends and directional influences. Kriging does not require the data under study to have a normal distribution; however, when the data are normally distributed, it is the best predictor from all unbiased predictors (Johnston et al., 2001).

3.3.1 Data Normality

One of the most used techniques to visually inspect data normality and outliers is the frequency graph or histogram. One histogram was plotted for each coffee quality attribute and data normality tests showed the following results: all of the histograms illustrated a unimodal and nearly symmetric graph (Figure 3.2) indicating the data distribution was normal. Skewness values ranged from 0.1 to 0.4. In addition, the mean and median values were very similar for each quality attribute and no outliers were detected (Table 3.1).

After revising all the results from the histograms (Figure 3.2) and Table 3.1, the data for this study were considered to have a normal distribution and therefore no transformation was applied. A trend analysis test showed a light trend in the east-west path and a little stronger trend in the north-south direction was detected. All the quality attributes presented similar trend results.
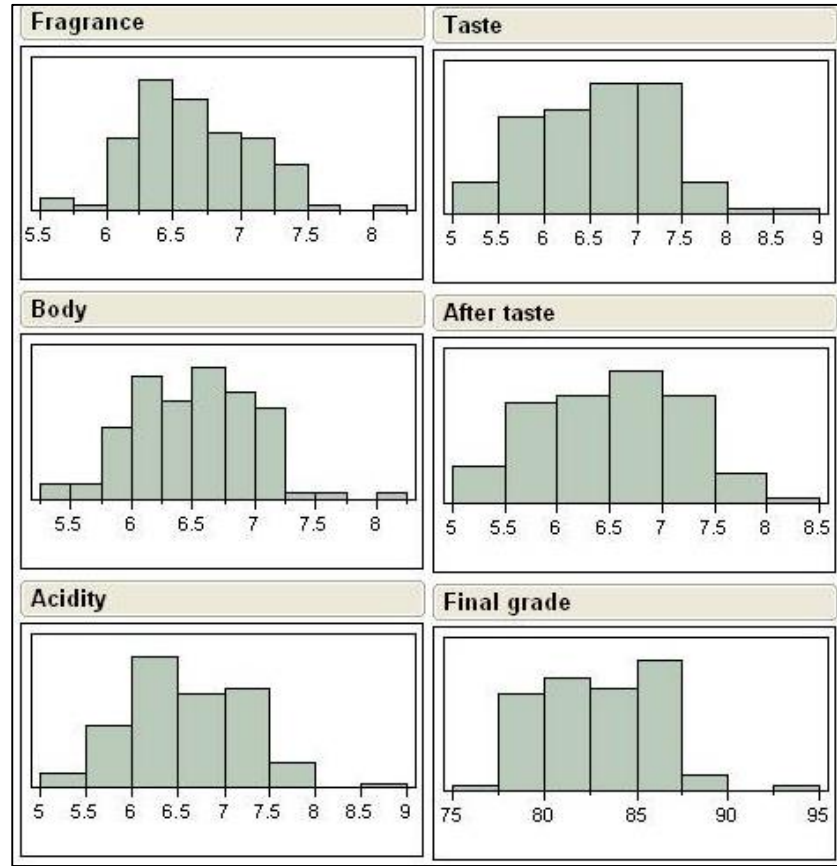
Figure 3.2: Histograms for the coffee quality attributes

Table 3.1: Descriptive statistics for the coffee quality attributes

Attribute	N	Min	Max	Mean (μ)	Median	Mode	Skewness	Kurtosis
Fragrance	83	5.6	8.2	6.63	6.6	6.9	0.43	0.40
Body	83	5.4	8.0	6.48	6.5	6.4	0.18	0.06
Acidity	83	5.2	8.5	6.55	6.5	6.4	0.23	-0.16
Taste	83	5.1	8.6	6.54	6.55	6.5	0.20	-0.32
After-taste	83	5.1	8.45	6.47	6.5	6	0.13	-0.52
Final grade	83	76.45	93.35	82.9	82.7	81.1	0.38	0.08

3.4 Fitting a model to the Empirical Semivariogram

As stated in the objectives of this study, the following three models will be compared: Spherical, Exponential, and Gaussian. Although the semivariogram accounts for spatial autocorrelation, it does not provide an explanation for autocorrelation in different directions and does not guarantee that positive kriging variances will be the outcome from the kriging predictions. Hence, it is necessary to fit a model to determine semivariogram values at different distances (Jakubek, 2002).

3.4.1 Spherical, Exponential, and Gaussian Models

The spherical model is probably one of the most common models used in kriging. This model usually shows a linear behaviour at small distances near the origin, but flattens out as these distances increase. The exponential model is linear at short distances near the origin (Isaaks and Srivastava, 1989) and exhibits a decrease in spatial autocorrelation at increasing distances (Jakubek, 2002). The Gaussian model is a transition model frequently used to model continuous phenomena. A unique characteristic of this model is the parabolic behaviour near the origin (Isaaks and Srivastava, 1989).

The distance where the model flattens out is called the "range" and the value at the point where the range begins is known as the "sill". The nugget effect arises when the model does not intersect the origin, but crosses the "Y" axis at some value greater than zero (Figure 3.3) (Jakubek, 2002). The nugget effect is composed by the variance of measurement errors in combination with variation from sources at spatial scales that are too fine to detect (Burrough and McDonnell, 1998). A larger nugget effect tends to make

the estimation procedure more like a simple averaging of the dataset. In the presence of a pure nugget effect there is lack of spatial correlation and this is an undesirable scenario for the application of the ordinary kriging technique (Isaaks and Srivastava, 1989).
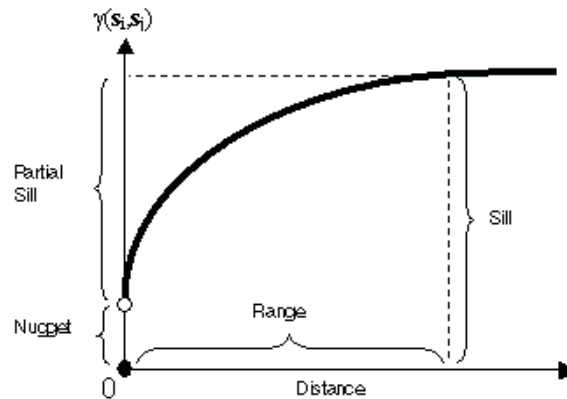
Figure 3.3: Typical semivariogram Source: ESRI, 2008

3.4.2 Determining the Search Neighbourhood

Kriging is commonly known as a minimum variance estimator, but this is only true when the neighbourhood is properly defined. The size and shape of the search neighbourhood and the number of neighbours to be used will have a significant impact on the predicted surfaces. Using default values is very risky because the kriging weights are directly associated to the variogram, data geometry, and sample support (Vann et al., 2003).

Although for many people the everyday cup of coffee may taste the same, in nature, coffee quality attributes vary even between closely situated farms, but higher variations in quality attributes are found as the distance between coffee farms increases (Funez, 2006). This complies with the first law of geography: "Everything is related to everything

else, but near things are more related than distant things" (Isaaks and Srivastava, 1989). This variation in quality attributes is due to a combination of many factors, such as microclimate conditions, canopy coverage, and elevation among others (Luttinger and Dicum, 2006).

The size of the search neighbourhood and the number of locations to be used for the predictions were optimized in order to exclude samples that were too far away and therefore have minimal influence on the overall prediction (Isaaks and Srivastava, 1989). An elliptical shape was chosen to account for the north-south pattern (Jakubek, 2002) and four sectors were selected in order to avoid bias in a particular direction (Johnston et al., 2001). The major and minor ranges were set to 25000 and 15000 m respectively. The maximum number of neighbours was limited to 10 and the minimum to 2. This is similar to Vann et al. (2003) that recommended not limiting the search neighbourhood to the range of the variogram. In addition, they suggest using at least 10-12 neighbours as the maximum number to include.

The lag size has an important influence in the empirical semivariogram. If the lag size is too large, short range autocorrelation may be masked. If the lag size is too small there may be many empty bins and the sample size in some bins could be too small to get representative averages. When samples have a gridded arrangement, the grid spacing is usually a good indicator for lag size. However, if the data were acquired using a random sampling design, like in this study, a general guideline is to use a multiplication ratio

between lag size and the number of lags that is about half the largest distance among all measurements in the dataset (ESRI, 2008).

3.4.3 Anisotropy

Anisotropy can be described as a random process that shows stronger autocorrelation in one specific direction. It is typically not a deterministic process that can be explained by a single mathematical formula (Johnston et al., 2001). For this study, anisotropy was detected by activating the "show search direction box" (in the geostatistical wizard) and testing numerous directions. The angle that offered the most autocorrelated semivariogram was selected. For this dataset the angle was defined at 355 degrees.

3.5 Cross-Validation: Recognizing the Best Model

Cross-validation is a procedure that allows for the comparison of estimated and true values using only the information available in the sample dataset. With cross-validation, many weighting procedures and variogram models can be compared in order to make an informed decision about the best prediction (Johnston et al., 2001).

Cross-validation uses all the points in the dataset in order to estimate the autocorrelation model and then it eliminates one data location and forecasts the data value for that location. This procedure is repeated for all the points in the dataset. By doing this the observed value can be compared to the predicted value and this difference ratio is called the "error statistic". This allows an evaluation of the accuracy of the kriging model parameters (semivariogram and search neighbourhood settings). If the model is a good

illustration of the spatial variability, then the error statistic should have a normal distribution with the mean close to zero and the standard error close to one (Houlding, 2000).

In summary: the mean prediction error (MPE), which should be as close to zero as possible (Dennis and Forsythe, 2007); the mean standardized prediction error (MSPE) also has to be near zero (ESRI, 2006); the root mean square prediction error (RMSPE) and average standard prediction error (ASPE) should be less than 20 and their difference ratio (RMSPE-ASPE) ought to be close to zero; and finally the standardized root mean square prediction error (SRMSPE) has to be close to one.

Chapter 4: Results and Discussion

In this section, the statistics obtained from cross-validation using the spherical, exponential, and Gaussian models will be compared. The model with the best statistics will be selected to make the prediction maps for the coffee quality attributes. Furthermore, each coffee quality attribute map for the Montecillos mountain range will be plotted and discussed.

4.1 Cross-Validation Results and Interpolated Surfaces

In ordinary kriging, the cross validation results can be used to compare the accuracy of the predictions made by each of the models. Specifically, the precision of each method is measured through the following prediction error values 1) MPE, 2) RMSPE, 3) ASPE, 4) SRMSPE, 5) MSPE, and 6) RMSPE – ASPE. Prediction errors 1 to 5 are computed by ArcGIS. RMSPE-ASPE had to be calculated separately by subtracting the RMSPE from the ASPE values.

All the coffee attribute predictions were obtained using ordinary kriging with the Gaussian model. Each prediction map was fit to the boundaries of the area of interest and the legend was divided in intervals of 0.25 units, except for the final grade map that was divided every 2 units. In addition, the same colour range was used for all the maps, where the light and dark yellows symbolize the lower quality farming areas, light and dark green for the medium quality coffee zones, and dark and light turquoise represent the higher quality coffee production areas. As elevation is an important variable in coffee quality, information about the elevation ranges in Montecillos is shown in Figure 4.1.
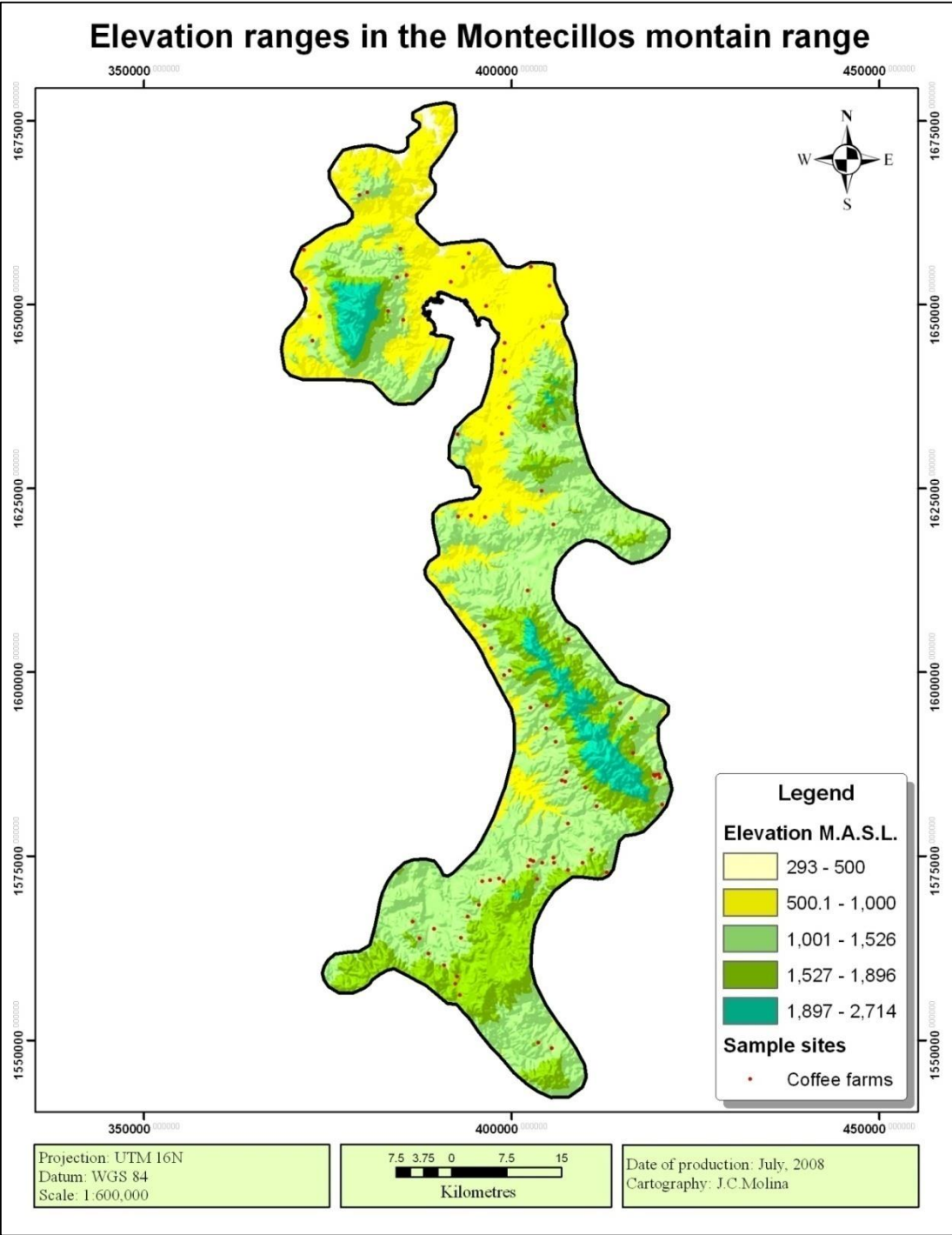
Figure 4.1 Elevation ranges in the Montecillos mountain range

Accurate (RMSPE-ASPE≈0) and unbiased (MPE≈0) prediction surfaces were produced for all the coffee quality attributes. However, all the SRMSPE values are slightly over 1, which indicates an underestimation of the variability by the model (ESRI, 2006).

4.1.1 Cross-Validation and Interpolated Surface for Fragrance

The cross-validation results for "fragrance" showed that the Gaussian model provided the best prediction error values (Table 4.1). The RMSPE value is close to optimal (Johnston et al., 2001) since it is the lowest (0.4601) among the models. In addition, the MPE is close to zero (0.0035), the SRMSPE is near 1 (1.009) and the RMSPE-ASPE value is the smallest, (0.0043) which indicates this model is the most accurate (Dennis and Forsythe, 2007) and the standard errors are appropriate (Johnston et al., 2001).

Table 4.1: Cross-validation results for Fragrance

	MPE	RMSPE	ASPE	MSPE	SRMSPE	RMSPE-ASPE
Spherical	0.00303	0.4604	0.4544	0.006381	1.012	0.006
Exponential	0.00325	0.4613	0.4542	0.006919	1.014	0.0071
Gaussian	*0.00356*	*0.4601*	*0.4558*	*0.007308*	*1.009*	*0.0043*

The coffees with the best fragrance (Figure 4.2) are found in the southernmost portion of the study area. Coffees with good fragrance are located in central, southern, and northern regions. Those areas in light green and yellow in the north of the Montecillos represent areas that may produce coffee with lower fragrance intensity.

Coffee fragrance predictions using Ordinary Kriging

350000 ₀₀₀₀₀₀   400000 ₀₀₀₀₀₀   450000 ₀₀₀₀₀₀

Legend

Fragrance

- 6.0 - <6.25
- 6.25 - <6.50
- 6.50 - <6.75
- 6.75 - 7

Sample sites

• Coffee farms

Projection: UTM 16N
Datum: WGS 84
Scale: 1:600,000
Date of production: July, 2008

7 3.5 0   7   14
Kilometres

Prediction errors
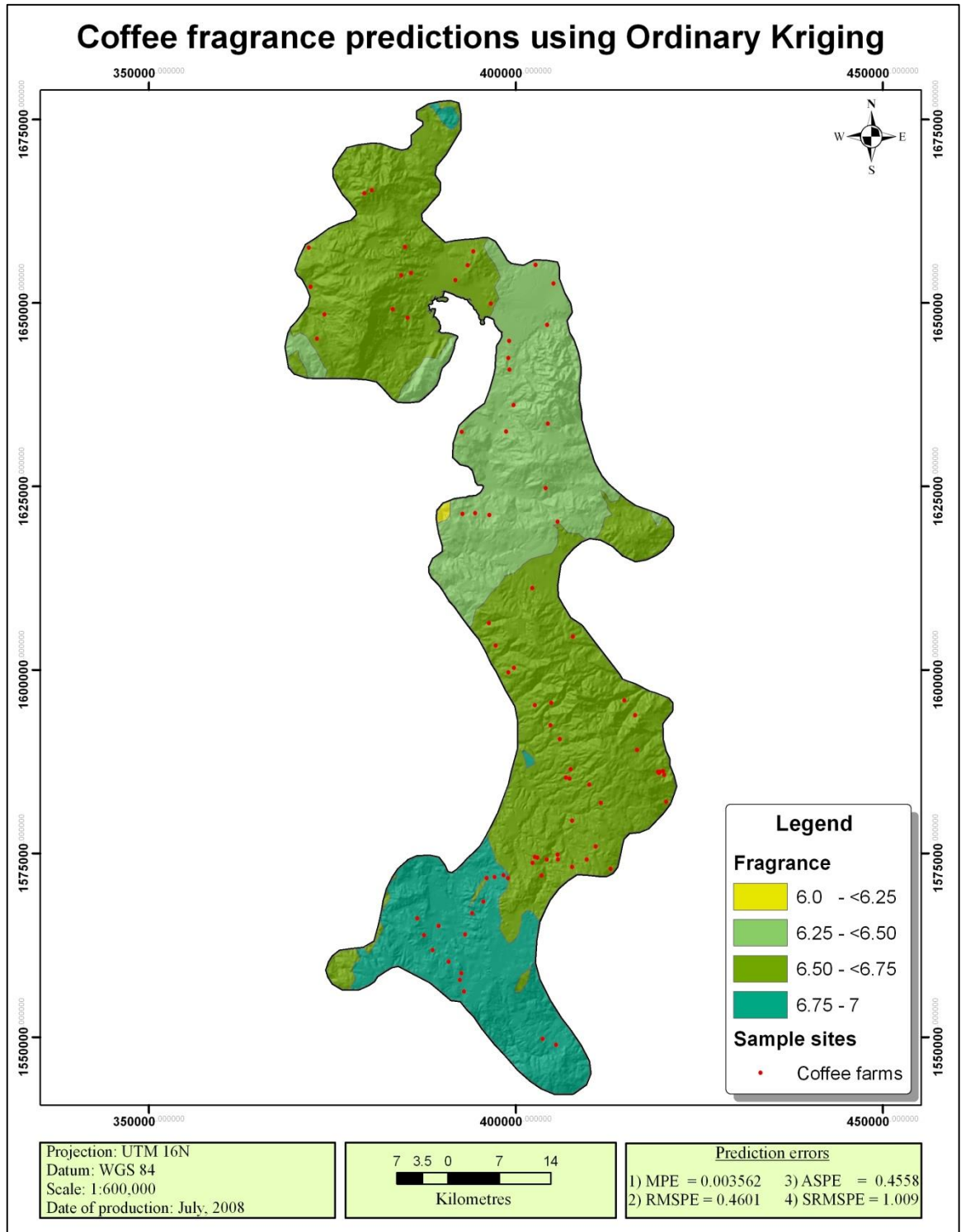1) MPE = 0.003562   3) ASPE = 0.4558
2) RMSPE = 0.4601   4) SRMSPE = 1.009

Figure 4.2: Coffee fragrance predictions using ordinary kriging

4.1.2 Cross-Validation and Interpolated Surface for Body

Table 4.2 contains cross validation statistics for "body". For this variable, the Gaussian model presented the best statistics. The RMSPE value is close to optimal (0.4865), the MPE is near zero (-0.003), the SRMSPE is close to 1 and the RMSPE-ASPE value (0.0373) indicates that this model is more accurate than the others.

Table 4.2: Cross-validation results for Body

	MPE	RMSPE	ASPE	MSPE	SRMSPE	RMSPE-ASPE
Spherical	-0.00388	0.4915	0.4456	-0.00404	1.091	0.0459
Exponential	-0.00344	0.4989	0.4381	-0.00288	1.119	0.0608
Gaussian	*-0.00303*	*0.4865*	*0.4492*	*-0.00289*	*1.075*	*0.0373*

Figure 4.3 shows the prediction results for coffee body. The coffee with the best physical properties or body is found in those areas with values greater or equal to 6.75, which are located in central and southern regions of the study area. Good coffee body values can be found in the dark green areas. Medium and low body values can be found in areas of lower elevation in central and northern portions of the Montecillos.
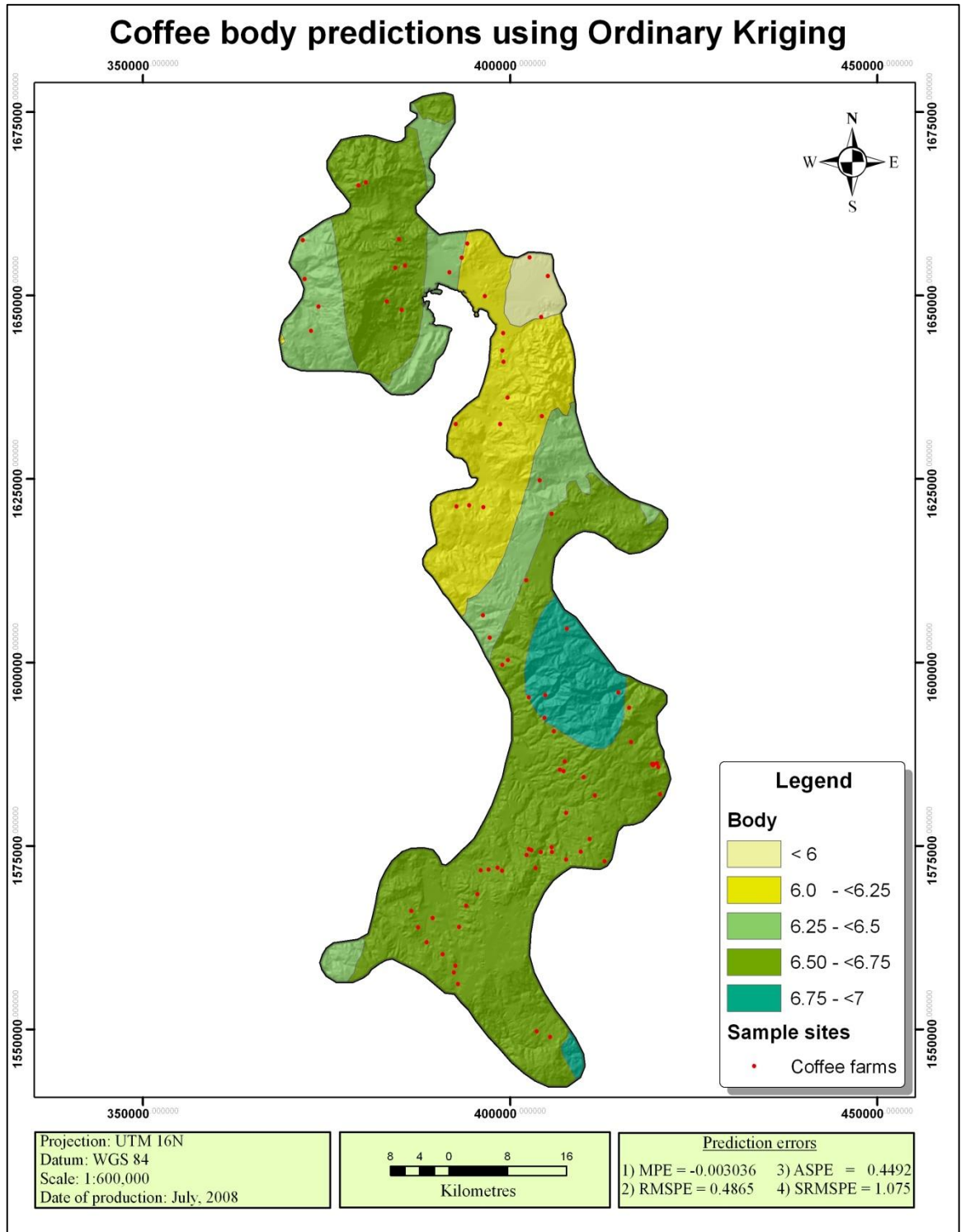
Figure 4.3 Coffee body predictions using ordinary kriging

4.1.3 Cross-Validation and Interpolated Surface for Acidity

Cross validation statistics for "acidity" (Table 4.3) also favour the Gaussian model as the model with the best error values. This is due to the best RMSPE value (0.6274) and RMSPE-ASPE difference ratio (0.0511). Also, the MPE is close to zero (-0.006156) and the SRMSPE (1.081) is in close proximity to 1.

Table 4.3: Cross-validations results for Acidity

	MPE	RMSPE	ASPE	MSPE	SRMSPE	RMSPE-ASPE
Spherical	-0.00747	0.633	0.5717	-0.00817	1.096	0.0613
Exponential	-0.00670	0.6406	0.5628	-0.00685	1.123	0.0778
Gaussian	*-0.00615*	*0.6274*	*0.5763*	*-0.00659*	*1.081*	*0.0511*

Acidity has a broader range of values (Figure 4.4) than the other attributes maps. However, it displays a similar quality distribution pattern observed for fragrance and body. The best coffee acidity is in the central part of the mountain range, as well as a couple of places in the south and one small area in the north. Good acidity values are located in the northern, central, and southern parts of the Montecillos. Lower acidity values are located in the central and northern portions of the mountain range. Most of these lower acidity areas have elevation values below 1000 metres (Figure 4.1).
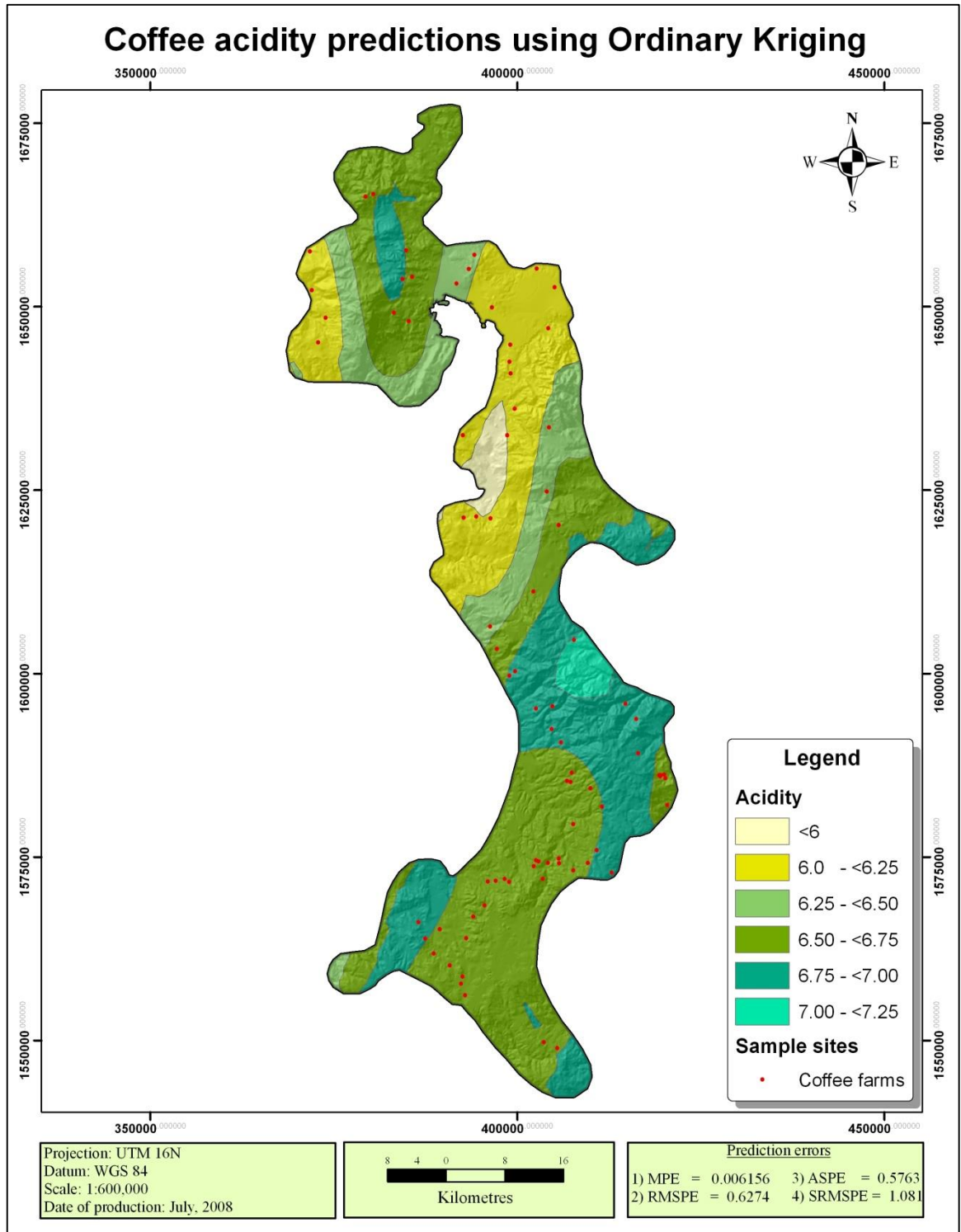
Figure 4.4 Coffee acidity predictions using ordinary kriging

4.1.4 Cross-Validation and Predicted Surface for Taste

The three models presented very similar cross-validation statistics for "taste". However, the Gaussian model offered the best predictions values (RMSPE= 0.6775, RMSPE-ASPE=0.0213, MPE=0.009212 ≈ 0, SRMSPE=1.03 ≈ 1) and therefore, was the most accurate model. Results for taste are summarized in Table 4.4.

Table 4.4: Cross validation results for Taste

	MPE	RMSPE	ASPE	MSPE	SRMSPE	RMSPE-ASPE
Spherical	0.007696	0.7011	0.6738	0.0116	1.038	0.0273
Exponential	0.008634	0.7044	0.6738	0.01298	1.042	0.0306
Gaussian	*0.009212*	*0.6988*	*0.6775*	*0.01334*	*1.03*	*0.0213*

One of the most important quality attributes in coffee is the taste, and the coffees with the best taste in the Montecillos were predicted in a small central region and scattered areas in the south. Good coffee taste was located in the central and most of the southern parts of the study area. Lower coffee taste values were predicted in the majority of the northern part of the Montecillos (Figure 4.5).
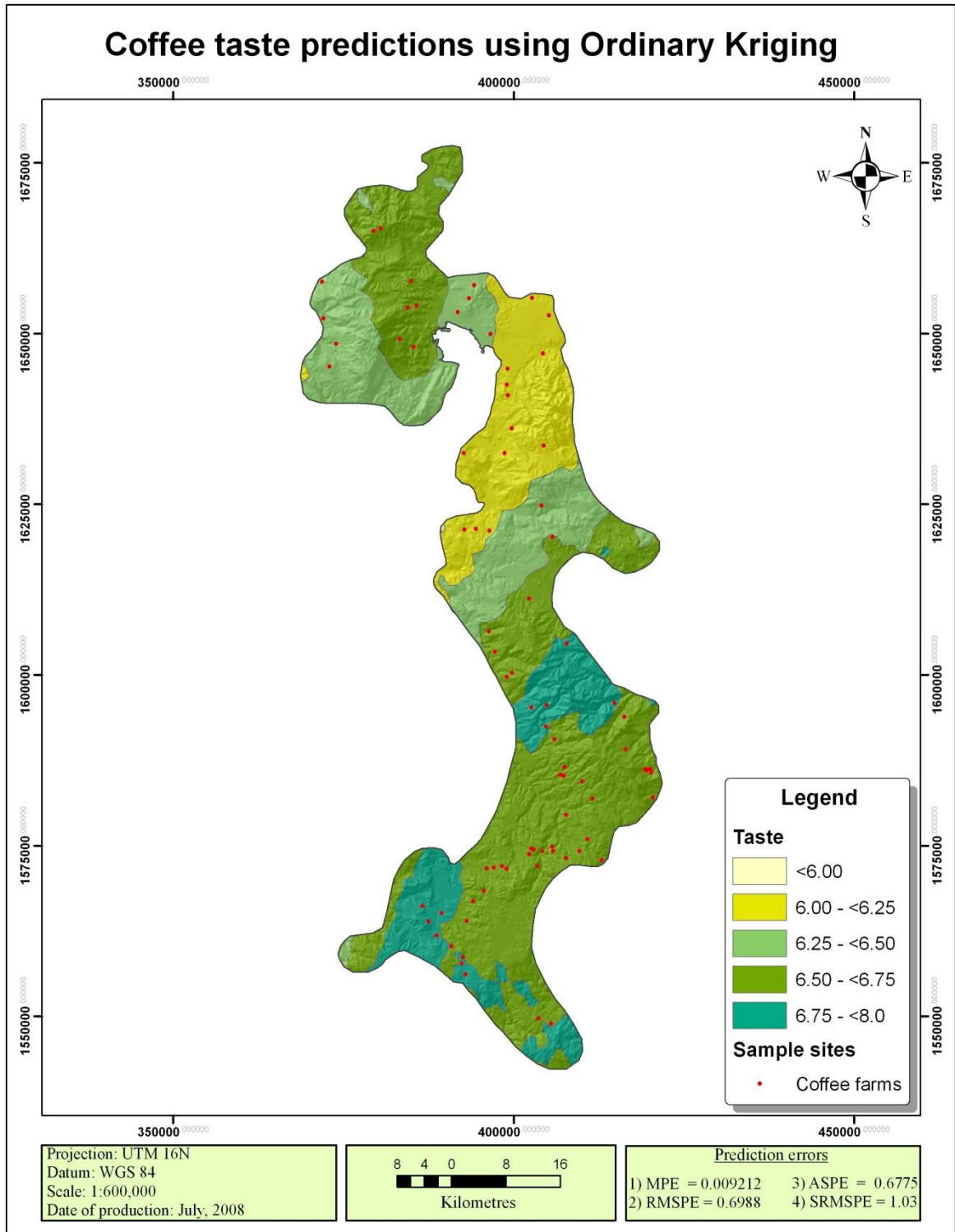
Figure 4.5 Coffee taste predictions using ordinary kriging

4.1.5 Cross-Validation and Interpolated Surface for Aftertaste

Cross-validation statistics for "aftertaste" showed better error values when using the Gaussian model (Table 4.5). This model provided the smallest RMSPE (0.7064) and RMSPE-ASPE difference value (0.017). Furthermore, the MPE is near zero (0.009212) and the SRMSPE is close to 1.

Table 4.5: Cross-validation results for Aftertaste

	MPE	RMSPE	ASPE	MSPE	SRMSPE	RMSPE-ASPE
Spherical	0.01013	0.7076	0.6861	0.0147	1.029	0.0215
Exponential	0.0112	0.7104	0.6863	0.01618	1.032	0.0241
Gaussian	*0.01164*	*0.7064*	*0.6894*	*0.01647*	*1.023*	*0.017*

The kriging method used in this study showed (Figure 4.6) that coffees with the best aftertaste in the Montecillos could be found in a couple of small areas in the south and in two small closely situated spots in the central part of the mountain range. Coffees with a good aftertaste were located in the north, central, and most of the southern portions of the Montecillos. Lower coffee aftertaste values were mainly found in the north, specifically in areas at lower elevations.
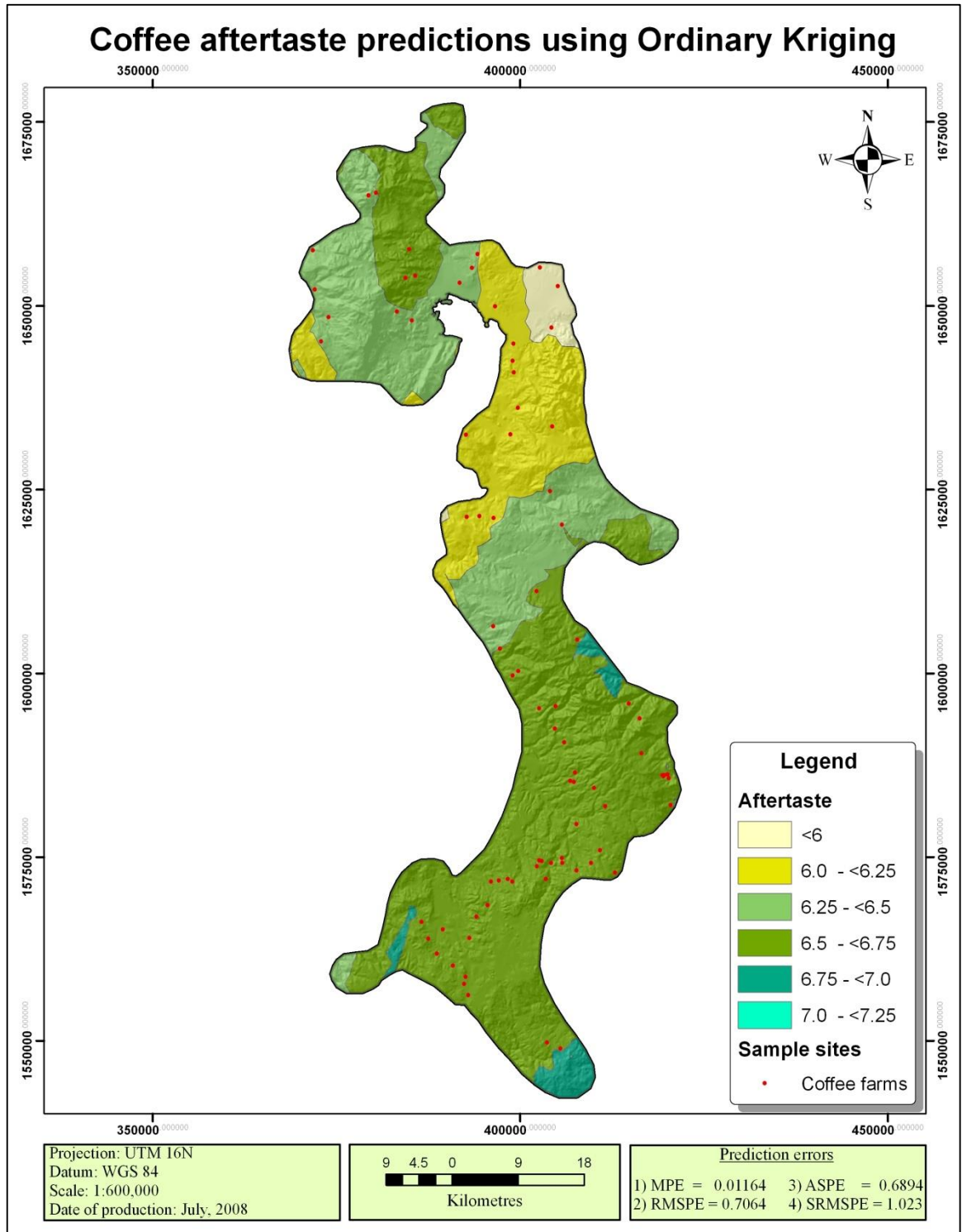
Figure 4.6 Coffee aftertaste predictions using ordinary kriging

4.1.6 Cross-Validation and Interpolated Surface for Final Grade

Cross validation results for "final grade" are presented in Table 4.6. As with the previous variables, the Gaussian model presented the lowest RMSPE (3.135) and RMSPE-ASPE (0.091) values and proved to be the most accurate model among the three. Also, the Gaussian model has other superior statistics, such as the MPE near zero (0.02511) and the SRMSPE value (1.028) close to 1.

Table 4.6: Cross-validation results for Final Grade

	MPE	RMSPE	ASPE	MSPE	SRMSPE	RMSPE-ASPE
Spherical	0.01818	3.146	3.028	0.006837	1.036	0.118
Exponential	0.02078	3.162	3.022	0.007797	1.042	0.14
Gaussian	*0.02511*	*3.135*	*3.044*	*0.008508*	*1.028*	*0.091*

The final grade or overall score is the most used quality value for coffee since it includes all the quality attributes. According to this score, coffees are classified as exemplary, very good and fair. The kriging technique used in this study predicted that outstanding coffees in the Montecillos come from central and southern areas (Figure 4.7). These regions could have the appropriate microclimate to produce specialty coffee. Very good coffees are found in the north, central, and most of the southern portions of the study area. Lower quality coffees are located in the central and most of the northern regions. Figure 4.8 shows the distribution of the final grade predictions draped over elevation in the study area.

Final grade predictions using Ordinary Kriging

350000 ᵒᵒᵒᵒᵒᵒ   400000 ᵒᵒᵒᵒᵒᵒ   450000 ᵒᵒᵒᵒᵒᵒ

1675000   1650000   1625000   1600000   1575000   1550000

N
W E
S

Legend

Final Grade
- 80 - <82
- 82 - <84
- 84 - 86

Sample sites
- • Coffee farms

Projection: UTM 16N
Datum: WGS 84
Scale: 1:600,000
Date of production: July, 2008

7 3.5 0   7   14
Kilometres

Prediction errors
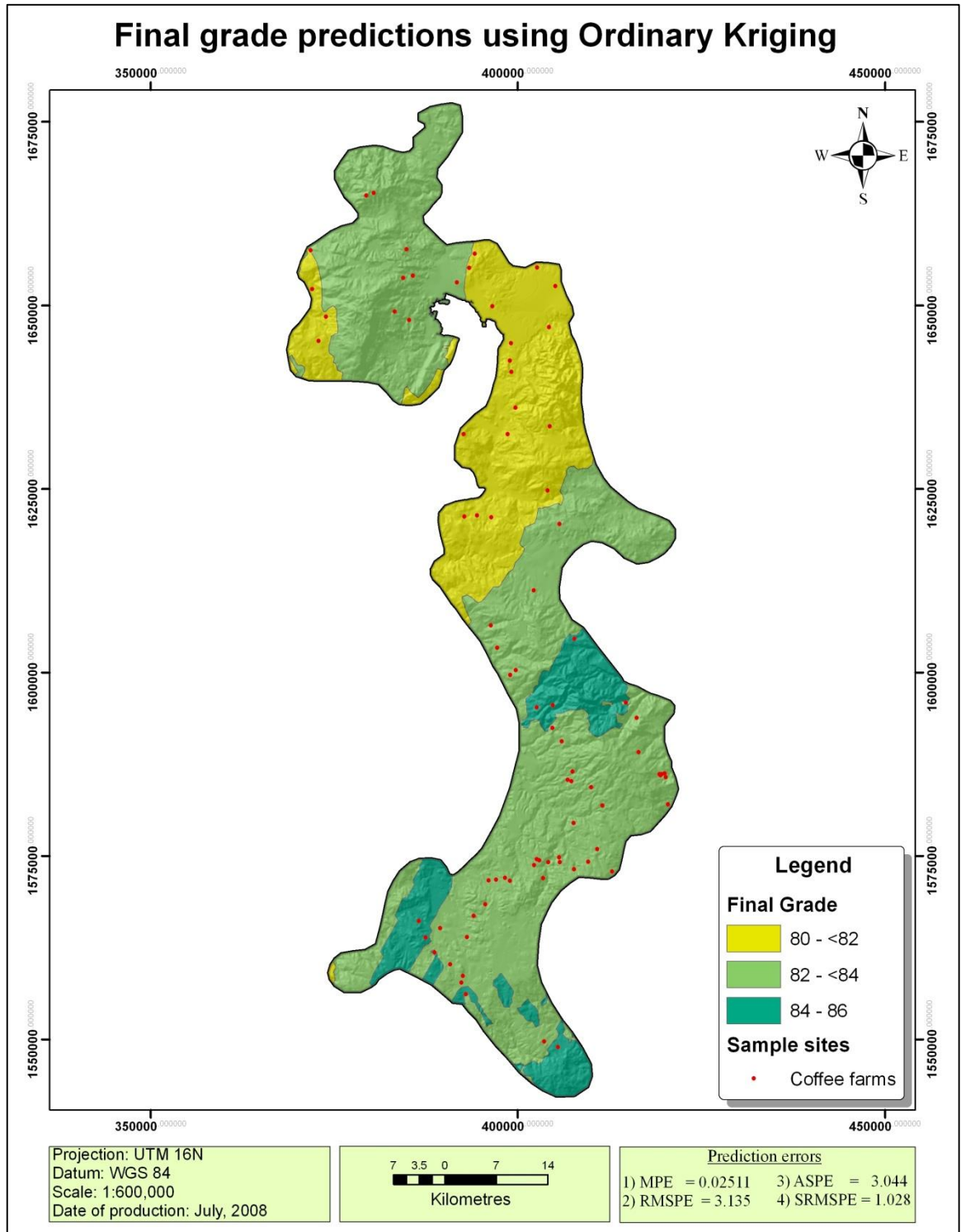1) MPE = 0.02511   3) ASPE = 3.044
2) RMSPE = 3.135   4) SRMSPE = 1.028
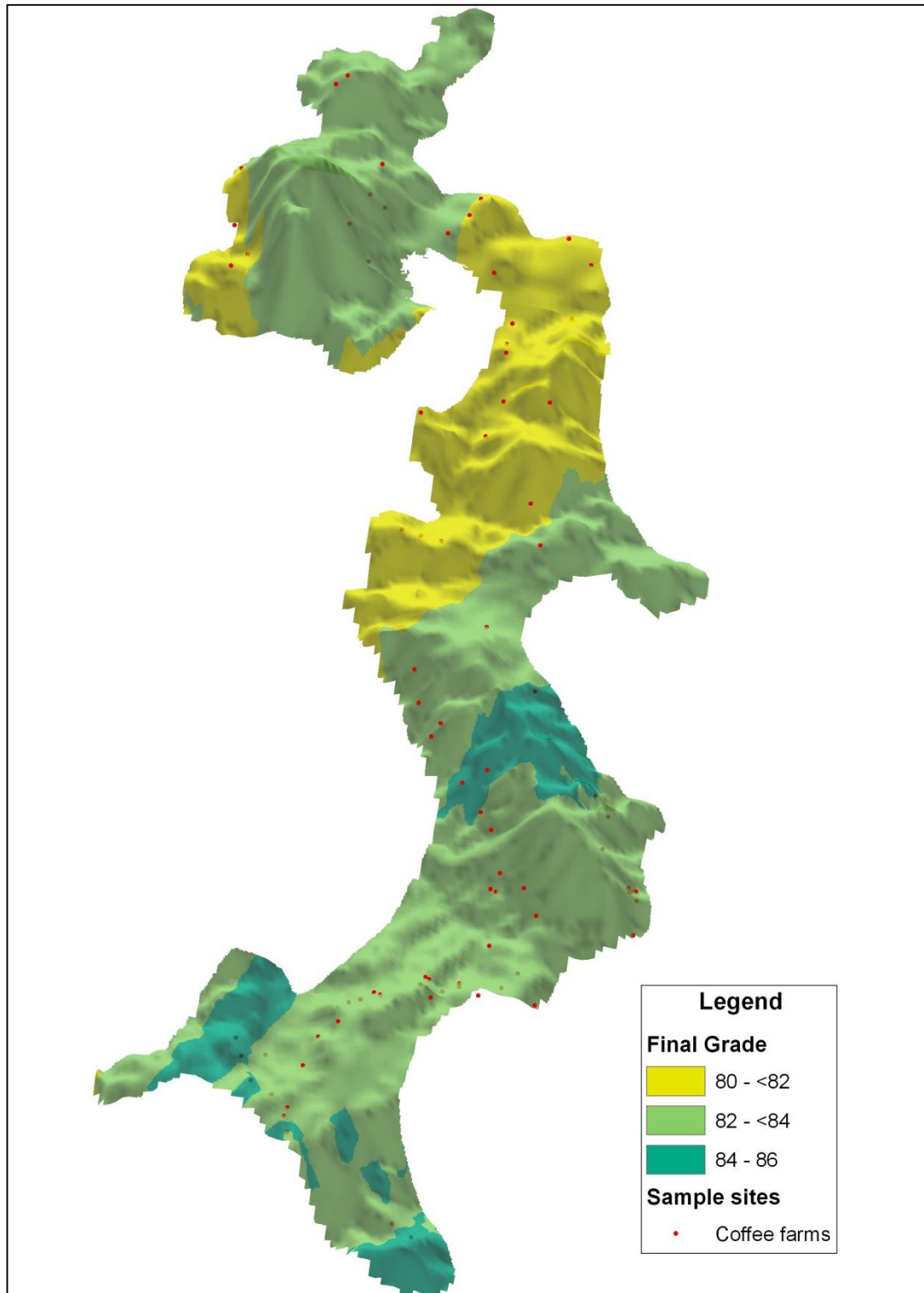
Figure 4.7 Final grade predictions using ordinary kriging

Figure 4.8: Final grade predictions and elevation in Montecillos

Chapter 5: Summary and Conclusions

Since it was discovered in the horn of Africa in the sixth century, coffee has become one of the favourite drinks in the world. Throughout history, coffee cropping and processing have been adapted in order to increase production and induce pleasant characteristics to satisfy dynamic coffee markets. In recent times, more emphasis has been put on the production of certified coffees (organic, fair trade, rain forest, etc.) and specialty coffees. One of the objectives of this study was to predict those areas in Montecillos that could produce these types of special coffees.

Interpolations in this study were carried out using three ordinary kriging models (spherical, exponential, and Gaussian). This method was selected over deterministic methods because it incorporates autocorrelation among the measurements and produces cross-validation statistics that allow for informed decisions about the model with the best predictions.

Statistics from the three models were compared and the Gaussian model was selected because it provided the best SRMSPE values. In addition, other cross-validation statistics values (ASPE, MSPE, and RMSPE) were used as indicators of accuracy. All the statistics obtained from cross-validation were significant. Fragrance was the variable with the best statistics and final grade had the least accurate, but still very strong statistics.

The methodology used for collecting and processing the coffee and analyzing the data proved to be successful in generating statistically significant results. However, due to the

influence of microclimate, soil, crop management and other components, it would be interesting to analyze and compare data from the same region obtained in a different time frame. Furthermore, smaller areas of interest inside the study area, such as those where the best coffee scores were found, could be targeted for a more detailed analysis.

Each of the prediction surfaces was classified from low to medium to high in terms of coffee quality. All the interpolated surfaces demonstrated a similar quality distribution pattern. The lower quality coffees are mostly located in the north and central parts of Montecillos. The good quality coffees are located in the far north and most of the southern portions of the study area. The best quality coffee zones are the smallest areas and are dispersed in the central and southernmost regions of the Montecillos. These small (10% of the study area) but highly interesting areas may have the potential to produce specialty coffees and these could be one of the most valuable resources in this region.

Specialty coffees, also known as gourmet coffees, are made of exceptional beans that grow in fertile soils in combination with unique microclimates. In July 2008, Honduras held their annual event of specialty coffees (Cup of Excellence) where the best coffees in the country are selected and sold to the highest bidder. The average price obtained per kilogram of coffee was more than five times the price of coffee being traded at the New York Board of Trade (USD 3/kg) at that time.

Good quality coffee areas cover approximately 64% of Montecillos. These results are very promising since this type of coffee is the most in demand in the world. In order to

keep offering the same cup of coffee year after year, coffee roasters look for beans free of cupping defects, good quality attributes, and consistency in the coffee lots. These characteristics are more likely to be found in these zones. In addition, many coffees from this category could show unique characteristics that may increase the final price through an incentive. Usually these incentives vary, but they could range between 0.22 to 1.3 USD per kilogram.

The lower score areas cover 26% of the study area. These yellow areas may produce a nice and clean cup of coffee, but they have less potential to offer coffees as aromatic or tasteful as in the other two zones. These coffees still find their way to international markets although they struggle to get incentives unless they have an added value such as a certification (for example, organic, fair trade or rain forest).

Coffee is a way of living for nearly 100,000 families in Honduras. This study may be used as a guideline for the distribution of coffee quality in the study area. In addition, it could serve as a tool to assist development plans for improving the living conditions of many coffee farmers. More research should be done in order to broaden knowledge about the spatial distribution of specific coffee attributes in the Montecillos mountains as well as in other coffee regions in Honduras.

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