7 Environmental Monitoring and Crop Water Demand

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7.1 Introduction[1]

Environmental monitoring refers to a stream of measurements and observations of the different characteristics of the natural environment. It could be made up of measurement systems of different components of natural systems, evaluation of parameters related to air quality, meteorology, quantity and quality of soil and water, and so on. One of the most important applications of meteorological and vegetation monitoring is the determination of crop water requirements or consumptive use. All vegetation consumes water in transpiration and this process is closely linked to photosynthesis. Direct evaporation also converts liquid water to vapour and it is usual to lump both together as *evapotranspiration* (ET).

The estimation of crop water requirements or ET is a very important part of water management in agriculture, regional water balance studies and hydrological modelling. It is possible to measure ET but the methods are complicated and costly, so that it is usually estimated using mathematical models. The method most commonly used for estimating ET in irrigated crops consists of defining a reference value (ET_0) which represents the atmospheric demand (potential ET) and multiplying this by a crop factor (Kc) which characterizes the state of the vegetation. Reference ET (ET_0) refers to ET from a reference crop that is plentifully supplied with water, and is usually obtained using some version of the Penman equation using meteorological information from a nearby climate station. The crop factor can be obtained from tables in which its value is related to the development stage of the crop. In order to obtain a good estimate of Kc, these values should be calibrated using local data. Nowadays, monitoring of vegetation condition can be conveniently carried out using sensors on board various spacecraft (Earth Observation Satellites), so that it should be possible to estimate the crop factor using spectral vegetation indices.

This chapter includes more than 10 years of studies in north-west Mexico, where measurement campaigns have been conducted for wheat, cotton, safflower, sorghum, potatoes, beans, chili, grapes and pecans using the aerodynamic method or 'eddy covariance'. In this way crop factors have been obtained for a wide variety of crops, which were then related to vegetation indices derived from satellite data at diverse spatial, spectral and temporal resolutions. Results show that it is possible to map ET over large areas (e.g. an entire irrigation district) using standard meteorological data from the network of climate stations together with remotely sensed data from satellites.

Environmental monitoring refers to a system for continuous observation and measurement of characteristics of the natural environment, allowing the evaluation of the observed changes and forecasts of future ones. During the 1960s, the severe environmental deterioration in many parts of the world was finally recognized, and with it, the need for records of environmental observations, and this led to the establishment of several environmental networks (Meadow et al., 1972). These monitoring systems cover different components of the environment: atmosphere, biosphere, hydrosphere and lithosphere, monitoring variables such as air quality, water and soil (quantity and quality), and many others.

Specifically, among the main hydroclimatological and vegetation monitoring objectives is the use of data for crop water needs assessment, in order to attain more efficient water use and better natural resources management. The aim of this work is to demonstrate that it is possible to monitor water use by vegetation (including crops) in real time, combining remotely sensed images with data from hydrometeorological networks. The micrometeorological group at the *Sonora Institute of Technology* (ITSON) and the *University of Sonora* (UNISON) started to work to-

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gether about 15 years ago and results from this period are presented here.

7.2 Meteorological Networks

Atmospheric and meteorological measurements have a long history in Mexico, going back several centuries. More recently, the *National Meteorological Service* (SNM) was established in 1901 with its own meteorological observatories and stations transmitting climatic data by telegraph. Afterwards, SMN was absorbed by the *Ministry of Water Resources* (SRH) and now is part of the *National Water Commission* (CONAGUA). An important responsibility of SMN is to maintain a national database and provide public access to meteorological and climatic information, as well as the realization of other meteorological and climatic studies. Thus, the infrastructure maintained by SMN includes more than 3000 meteorological stations, mostly manual, but including some automated stations.

Given the importance of hydrometeorological monitoring for agricultural activities and food production in Mexico, the federal *Ministry of Agriculture* (SAGARPA) has implemented a national network of agro-climatological stations, providing real-time meteorological data to help the agricultural sector and so improve the competitiveness of agribusiness. This network provides information to support farmers in improving their production, specifically in the application of irrigation water. The network contains more than 850 stations situated throughout Mexico.

7.3 Remotely Sensed Data

The constellation of *Earth Observation Satellites* (EOS) constitutes another system for environmental monitoring. These satellites carry diverse sensors that make continual observations of the earth (without the need to be in direct contact with it) in different regions of the electromagnetic spectrum. The observations consist of measurements of the energy reflected or emitted by objects on the earth's surface, or above it (clouds). The interpretation of these measurements is based a) on the distinctive spectral signature in which each object reflects the incident electromagnetic waves or b) on the quantity of energy emitted by the object as a function of its temperature, in accordance with the Stefan-Boltzmann law. Many different satellites and sensors have been used in environmental monitoring and table 7.1 shows a list (far from complete) of satellites and sensors in common use in Mexico. Three regions of the electromagnetic spectrum have been used most frequently: *visible* (VIS), *near infrared* (NIR) and *thermal infrare*d (TIR). The minimum time between observations of the same site (temporal resolution) varies from 15 minutes to 26 days. The smallest surface that can be observed by a satellite sensor (spatial resolution) varies from 2 metres to 4 kilometres.

Table 7.1: Characteristics of the principal satellites or sensors with possible application in the estimation of water use by vegetation. PAN refers to a panchromatic broad band with high spatial resolution**. Source:** Data from the authors.

Satellite/ Sensor	Spectral Bands	Resolution	
		Spatial	Temporal
GOES	TIR	4 km	15 min
	VIS	1km	15 min
MODIS	VIS/NIR	250 m, 500 m	1-2 days
	TIR	1 km	1-2 days
Landsat	VIS/PAN	30 m / 15 m	16 days
	TIR	60 m	16 das
SPOT	VIS/PAN	10 m / 5 m	5-26 days
FORMOSAT	VIS/PAN	8 m / 2 m	3-5 days

Generally, in the context of water use by vegetation, satellite remote sensors are mainly used to estimate the photosynthetically active ('green') biomass present at a particular site and to estimate the difference between the temperature of the vegetation and the temperature of the surrounding air, since this difference is related to the concept of vegetation water stress. In order to monitor vegetation 'greenness', spectral vegetation indices are commonly used. The most common is the *Normalized Difference Vegetation Index* (NDVI; Rouse et al., 1974):

$$NDVI = \frac{(\rho_{NIR} - \rho_R)}{(\rho_{NIR} + \rho_R)}$$

where ρ_{NIR} and ρ_{R} are reflectance for the near infrared band and the red band, respectively.

Figure 7.1: a) Real colour composite and b) evapotranspiration (W m^{-2}) for wheat in the Yaqui valley, Mexico for one day during the growing season of 2000**. Source:** Landsat bands 1, 2 and 3.

7.4 Environmental Monitoring with Remote Sensors

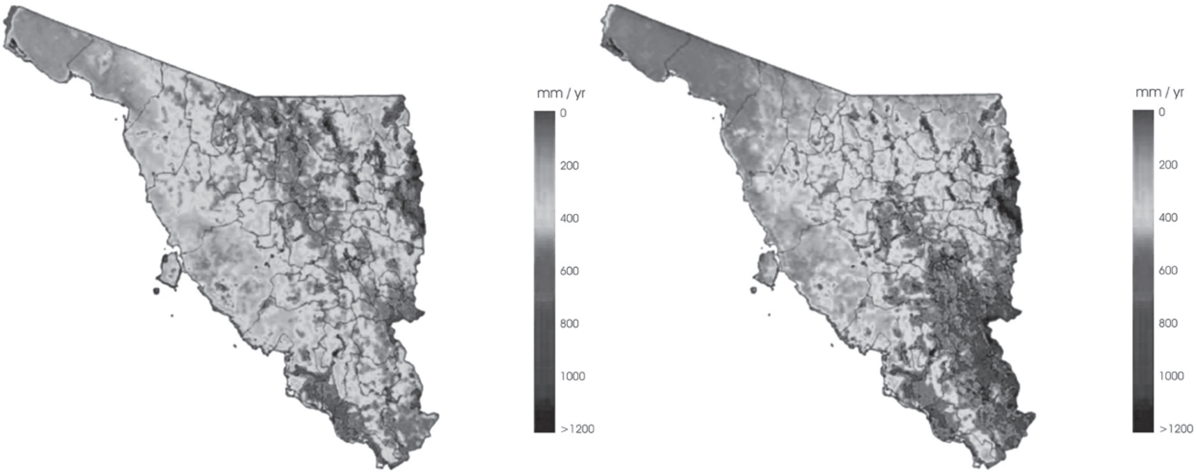
There are many examples of the use of remote sensing for environmental monitoring in Mexico. For example, Lobell et al. (2003) describe their experience using LANDSAT data to estimate wheat yields in the Yaqui valley, Sonora. Rodriguez et al. (2001, 2003, 2004) investigated the possibility of using MODIS data to forecast yields for 80 ha of wheat. Lobell and Asnar (2004) developed and tested a linear disaggregation approximation to estimate the fractional cover of different crops in one MODIS pixel, based on time series of spectral signatures during the growing season. They applied the technique in the Yaqui valley in Mexico and in the southern Great Plains in the USA, demonstrating the importance of sub-pixel heterogeneity in crop systems and the potential of temporal disaggregation for providing fast, reliable estimates of the spatial distribution of land cover using low spatial resolution images like MODIS.

Hudson and Colditz (2003) combined remotely sensed and geomorphic data to delineate the spatial extent of flooding in the lower Panuco River caused by a large hurricane in the Gulf of Mexico. Salinas-Zavala et al. (2002) analysed the relationship between the inter-annual variability of NDVI, rainfall and atmospheric circulation at 700 mb in northwest Mexico. They separated the data corresponding to the cold and warm phases of *El Niño Southern Oscillation* (ENSO) and found that the negative phase of ENSO was associated with drought conditions.

The application of remotely sensed data for estimating hydrological variables has a long tradition. In the early 1990s, Garatuza and Watts (1993) used VIS and IR data from the geostationary satellite GOES to estimate the extent of snow cover in the western Sierra Madre, and constructed a computational system for estimating other variables using GOES images provided by a receiving station installed at ITSON in Ciudad Obregon, Sonora (Stewart et al., 1995). These GOES images were used by Yucel et al. (1998) and Garatuza et al. (2001a) to obtain high resolution maps of cloudiness. Another application was the estimation of incoming solar radiation using GOES images from the receiving station at ITSON (Watts et al., 1995; Watts et al., 1999; Stewart et al., 1999; Garatuza et al., 2001b, 2001c). These studies provided new information about cloud cover in north-west Mexico and the use of this information in a new method of obtaining high resolution estimates for incoming solar radiation, an important variable in environmental monitoring for hydrological studies and integrated water management.

With regard to measurement, modelling, and estimation of evapotranspiration as an indicator of crop water requirements, various studies have been published (Garatuza et al., 1998, 2001d, 2003, 2005b; Garatuza and Watts, 2005; Mendez-Barroso et al., 2008; Unland et al., 1997), combining data collected in situ with remotely-sensed data of high and low spatial resolution (figures 7.1, 7.2). Additionally, experiments have been conducted to establish methods of estimating average surface fluxes over heterogeneous surfaces (Watts et al., 2001; Chehbouni et al., 2001, 2008).

Figure 7.2: Annual evapotranspiration in Sonora (a) October 1999 to September 2000 using NOAA-AVHRR images and (b) October 2002 to September 2003 using MODIS images. The outlines of municipal limits have been included. **Source:** Elaborated by the authors.



7.5 Crop Water Requirements

The estimation of crop water needs or *evapotranspiration* (ET) is an important issue in water management in irrigated agriculture, regional water balance studies and hydrological modelling. At the plot scale, estimates of ET are needed for irrigation scheduling and so form an integral part of decision support management tools (Abrahamsen/Hansen, 2000; Garatuza/Watts, 2005).

It is possible to measure the rate of ET in situ, but the equipment is expensive and the data collected in the field requires complicated processing procedures. For this reason, ET for irrigated crops is usually estimated as the product of reference ET (ET_0) that represents the 'atmospheric demand' and a crop coefficient Kc that reflects the vegetation condition (Garatuza/Watts, 2005):

$$ET = Kc * ET_0$$

where ET_0 refers to an "actively growing, well watered grassland (i.e. zero water stress) that completely covers the ground". ET_0 is usually calculated with some version of the Penman equation (Penman, 1948) that requires information about net radiation, air temperature and humidity, and wind speed. Unfortunately, many versions of this equation have been proposed and the method is sometimes not applied correctly, but the publication of FAO-56 (Allen et al., 1998) provides a convenient standardized version. So the correct estimation of ET requires the following data: characteristics and development stage of the crop, climate parameters, and management practices. The climate parameters are included in ET_0 while the others are included in the crop factor Kc.

7.5.1 Measurement and Estimation of Kc

The aforementioned factors are specific to each crop and change with crop development. Allen at al. (1998) subdivide the development stages of the crop into four phases: initial, development, stabilization and senescence, and presents tables with values of these coefficients for a large variety of crops, while recommending local calibration of the values. A great deal of work has been carried out to determine appropriate crop factors for different crops in different regions using different management practices. The determination of accurate estimates of Kc requires measurement of *actual* ET and the estimation (using climatic variables) of ET_0 so that

$$Kc = ET/ET_0$$

Some examples of the determination of Kc for different types of crops (annual, perennial, fruit trees, etc.) using different management practices (flood irrigation, drip irrigation, etc.) include Garatuza et al. (1998) who developed time dependent Kc for wheat and cotton under flood irrigation in the Yaqui valley based on *eddy covariance* (EC) measurements of actual ET; Benli et al. (2006), who used a weighing lysimeter to determine Kc for alfalfa in the semi-arid conditions of the Anatolian plains in Turkey; and Wanga et al. (2007), who used four different methods for measuring ET in an open pecan orchard to develop an equation for Kc as a function of effective vegetation cover. Hanson and May (2006) used the *Bowen Ratio Energy Balance* (BREB) method for estimating ET to obtain Kc for tomatoes under drip irrigation. They used a second-order relationship between Kc and vegetation cover, and developed curves describing the temporal variation of Kc for different sowing dates. Kang et al. (2002) used lysimeters to measure ET for wheat and corn in a semi-arid region of north-west China and developed a fifth-order polynomial relationship relating Kc to the number of days since sowing. Kjaersgaard et al. (2008) used EC to measure ET and net radiation measurements for ET_0 in a cold sub-humid region and found larger values for Kc than those previously used in that region. De Azevedo et al. (2007) used the BREB method for pineapples in tropical Brazil and found that Kc was dependent on the complex interaction of physiological factors and climatic conditions.

We can conclude from this list of examples – which is by no means exhaustive – that a great deal of effort has been made to determine crop factors all over the world, from cold to tropical climates; for a wide variety of crops, both perennial and annual; from complete soil cover to very sparse; from low crops to tall trees. Different management systems can be used for all of these and a wide variety of techniques are used to measure real ET. These studies provide a means of estimating Kc as a function of some variable that is relatively easy to obtain, such as time or fractional cover.

7.5.2 Estimation of Kc and ET with Remote Sensors

As mentioned previously, the measurement of real ET is difficult and requires expensive equipment and specially trained personnel, irrespective of the chosen measurement method: lysimeters, soil humidity balance, eddy covariance, etc. Moreover, the crop factors obtained from these studies cannot be applied universally, since crop development is not the same in different years or in different places (even using the same irrigation scheme), nor are management practices in every field. Therefore, we need to look for an alternative method to estimate Kc. The method should be easy and cheap to perform and provide near real-time estimates. Fortunately, the same factors that affect Kc also affect spectral vegetation indices, and many authors have investigated the relationship between them (Garatuza/Watts, 2005; Zwart et al., 2006; Jayanthi et al., 2007; Rodriguez et al., 2009; and many others).

The hydrometeorology group at ITSON and UNISON have been using eddy covariance techniques to measure real ET since 1994 (Garatuza et al., 1998) for crops and natural vegetation, using measurement protocols described in Scott et al. (2003) and Perez-Ruiz et al. (2009). The group has recently collaborated with researchers from CESBIO (*Centre d'Etudes de la Biosphere*) in a field programme to measure real ET for many crops in order to determine Kc and relate these to other variables such as the spectral vegetation indices obtained from satellite data. These studies were mainly carried out in the Yaqui valley and Costa de Hermosillo in Sonora. In the next section results are presented for the most important crops in the region.

7.5.3 Costa de Hermosillo

Measurements of real ET were performed using two EC systems during 2005–2006 for two grape varieties (Perlette and Superior) and pecan. Climate data were obtained from the network of *automatic weather stations* (AWS) operated by INIFAP, and ET_0 for each measurement site was obtained using average values for the climate parameters from the closest AWS, where each value was weighted by the inverse of the squared distance. All available LANDSAT images for this period were collected (a total of 17) and NDVI values were extracted corresponding to the EC measurement sites. The ratio of measured ET over ET_0 (measured Kc) was obtained for the day of the satellite overpass and compared to NDVI from LANDSAT (figure 7.3). Linear regression gives

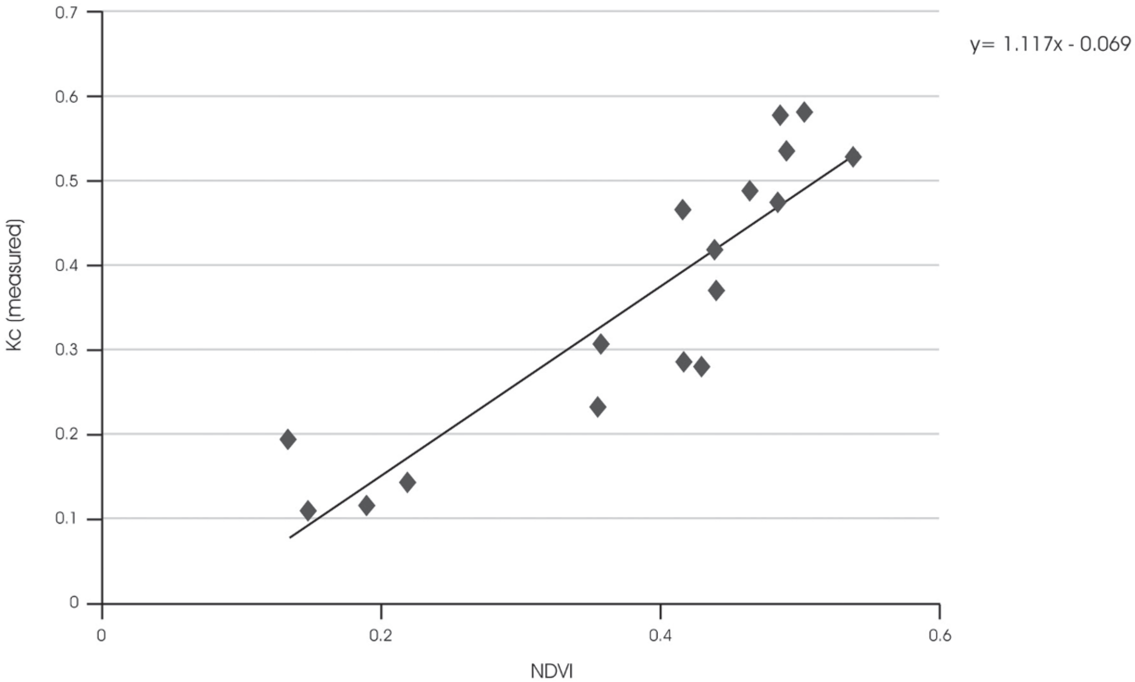
$$\frac{ET}{ET_0} = 1.117\,NDVI - 0.069 \qquad (r^2 = 0.8)$$

so that the slope is close to one and the intercept is close to zero. If the regression line is forced through the origin, we obtain a slope of 0.953 ($r^2 = 0.782$).

7.5.4 Yaqui Valley

During 2008 a large field campaign was conducted as part of the Pleiades project, to measure real ET using EC systems for seven different crops: broccoli, beans, chickpeas, chili peppers, potatoes, safflower and wheat. Crop development and management practices were carefully monitored and stored in a database. Satellite data were downloaded from the appropriate

Figure 7.3: Relation between Kc and NDVI for grapes in the Costa de Hermosillo during 2005 and 2006. The values of Kc were obtained using EC measurements of ET and ETo from local climate data. **Source:** Data elaborated by the authors based on NDVI obtained from Landsat 5 images.



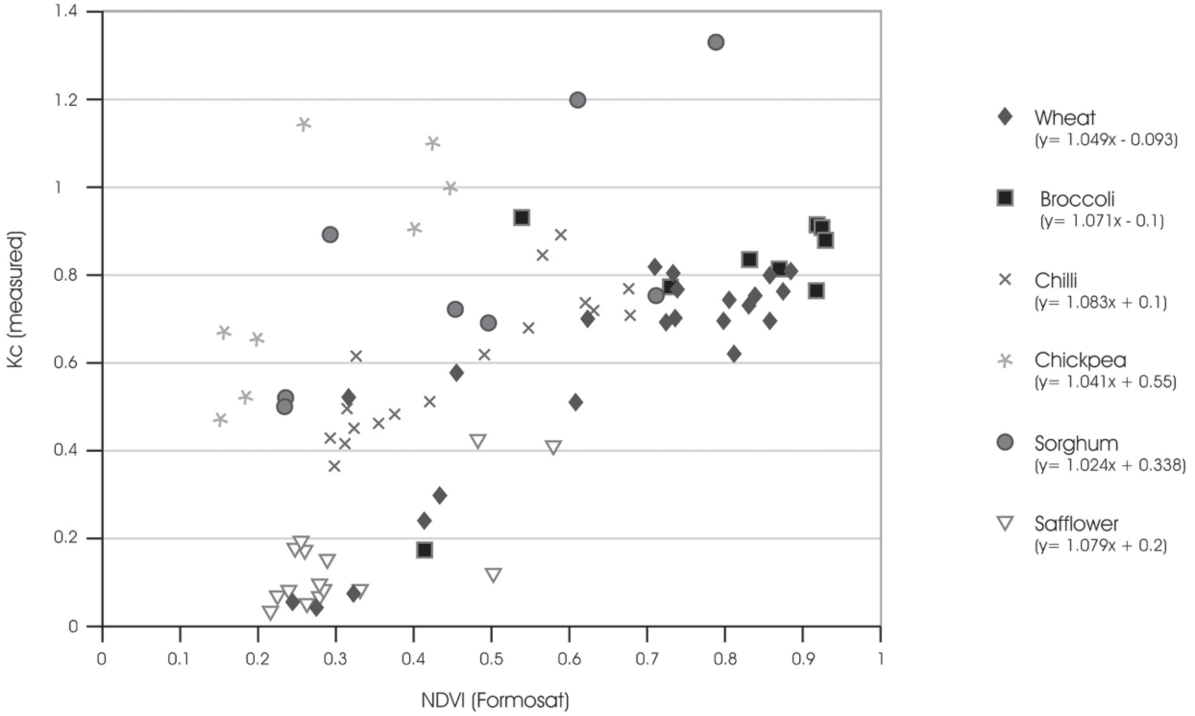
websites for Landsat, MODIS and GOES. The French Space Agency CNES (*Centre National d'Etudes Spatiales*) provided 40 images from the FORMOSAT satellite (8 metre spatial resolution) and NDVI values were extracted from these for each EC measurement site. ET_0 was calculated from data using the closest AWS (Block 1418) and Kc was calculated as the ratio of measured ET over ET_0. Figure 7.4 presents the results of relating measured Kc to NDVI. The slope and intercept for the linear regression line is shown for each crop. In each case, a line with slope equal to 1 provides a good approximation to the observed data, although not always the best one.

7.5.5 Spatial Distribution of Variables

In general, the measured values of ET and other meteorological parameters are representative of only a small area around the instrumented site. In contrast, the satellite images provide data for a large area around the site, so that they can be used to extrapolate the calibrated results at the measurement sites. The linear relationship expressing Kc as a function of NDVI can be used with GIS map algebra to obtain maps of Kc. Similarly, if a map of ET_0 is generated by interpolation between the values for each AWS in the area, then we can obtain a map of real ET as well. Figure 7.5 shows results for part of the Yaqui valley irrigation area for three days during the wheat-growing cycle in 2008. Only values for areas planted with wheat are shown and other crops have been masked out. The first column corresponds to 3 January at the beginning of the growing season, when the value is low (even zero in some places). The second column corresponds to 23 February when wheat is fully developed in the whole area, and the third column corresponds to 27 April in the final stage of the growing season, when most of the crop has become senescent. Note the distinctive 'stain' in the upper left of the images. In this zone, some external factors had prevented the crop from developing normally as in the rest of the area.

In the first row, NDVI maps obtained from Formosat are shown for the three dates. The values of NDVI are between 0 and 1, increasing with the amount of biomass on the surface. The second row shows maps of Kc, and the third row contains maps of actual ET (in mm d^{-1}) for the same dates. In the second column (23 February) Kc and ET have their highest values, with Kc around 1 and ET about 5-7 mm d^{-1}, corresponding to fully developed crops. By the third date (27 April) the vegetation is almost dry, while other areas, with later sowing dates or varieties with longer growing seasons, are still active. So both

Figure 7.4: Relationship between Kc and NDVI for six different crops in the Yaqui valley in 2008. Kc values were obtained from the ratio of measured ET (using EC systems) and ET_0. NDVI was obtained from Formosat images. The slope and intercept from linear regression are included for each crop. **Source:** Elaborated by the authors.



Kc and ET show a wide variation: 0.2–0.8 and 2–7 mm d^{-1} respectively.

7.6 Conclusions

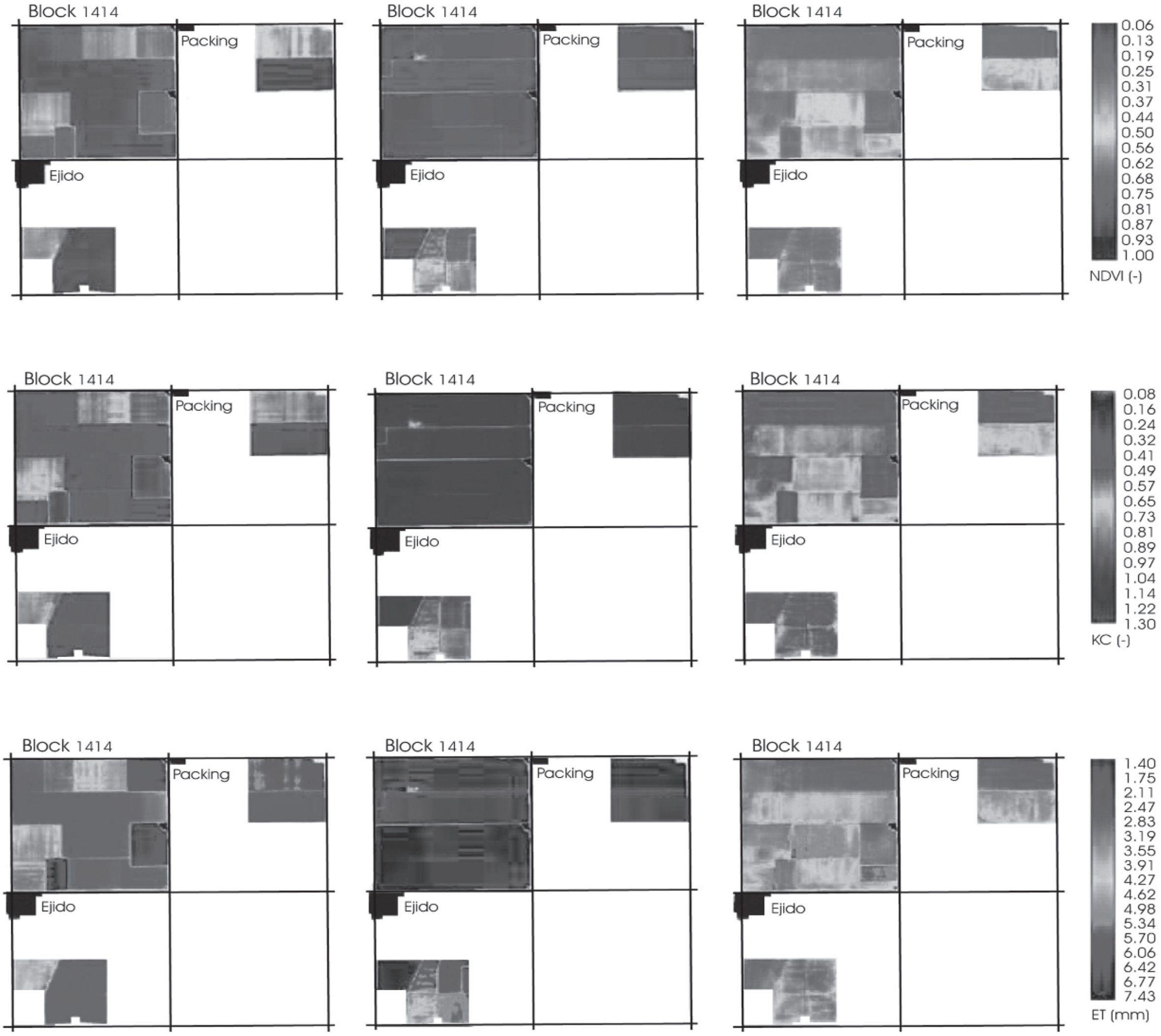
The estimation of water demand and use by crops is an important factor in the planning and operation of irrigation systems and also in hydrological studies to determine water availability in a region. Reliable methods to determine these are costly and complicated, so that it is common practice to use simple models instead, the most common of which is the two-stage model proposed by FAO. In this model, first the reference evapotranspiration (ET_0) is calculated using climate data collected from meteorological monitoring networks, and then the crop factor is determined.

The influences on crop factors are the same as those that affect spectral vegetation indices, generally based on the differences in the reflectance of the vegetation and soil in the red and near infrared bands of electromagnetic radiation. Therefore, it is possible to establish functional relationships between *vegetation indices* (VI) and *crop factors* (Kc), so that the latter may be estimated using routine observations from earth observation satellites.

The results of many studies carried out by the authors suggest that Kc can be represented as a linear function of VI with slope close to unity. The intercept is variable and depends on crop type and percentage cover.

These results indicate that a family of linear equations with unit slope and variable intercept (function of crop type and cover) could be used to provide near real-time estimates of Kc and ET with the necessary spatial and temporal resolution to be used operationally in irrigation scheduling. In order to accomplish this, it is essential that the climate data and remotely sensed data (from satellite, aircraft or other platforms) be available on time and the results be available online, so that the end users receive the information in a timely fashion. It is also important to maintain an up-to-date database with information on crop types, sowing dates, application of irrigation, fertilizer, etc.

Figure 7.5: NDVI (row1), Kc (row2) and actual ET (row 3) for three dates during the growing season for wheat in the Yaqui valley. Only values for the fields with wheat are shown; the others are blank. The three dates chosen are: 3 January (Column 1), 23 February (Column 2) and 23 April (Column 3). **Source:** Elaborated by the authors.



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