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Estimation of the Effect of Soil Salinity on Crop Yield Using Remote Sensing and Geographic Information System

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Abstract: This study was conducted to estimate the effect of salinity on crop yield by employing a geographical information system (GIS) and remote sensing technologies. The saline soils of Arıcan village, located in the southeastern part of Harran Plain, were studied. Surface soil samples representing each soil series in the study area were collected and analyzed to generate an electrical conductivity (EC) map of the study area soils. Using ground truth information, satellite images were classified and land use classes were determined in the study area. The EC map, land use map, soil map and parcel map were combined and analyzed in GIS media to estimate the effect of salinity on crop yield. The results showed that increasing EC values up to 13.4 dS m^{-1} caused decreases in cotton and wheat yield of 29.6 % and 35.4 %, respectively. Increases in salinity above the threshold for cotton and wheat resulted in a linear decrease in crop yields. The results indicated that remote sensing and GIS techniques are useful tools for estimating the effects of soil salinity on crop production as shown for wheat and cotton in the present work.

Key Words: Remote Sensing, GIS, relative yield, crop yield, salinity, EC

Uzaktan Algılama ve Coğrafi Bilgi Sistemi Kullanılarak Toprak Tuzluluğunun Ürün Verimi Üzerine Etkisinin Tahmin Edilmesi

Özet: Bu çalışma, uzaktan algılama ve coğrafi bilgi sistemi (GIS) teknikleri kullanılarak tuzluluğun ürün verimi üzerine olan etkisini tahmin edilmesi için yürütülmüştür. Harran Ovası'nın güney doğusunda yer alan Arıcan köyünün tuzlu toprakları çalışma alanı olarak seçilmiştir. Çalışma alanını temsil eden serilerin yüzey toprağından örnekler alınarak analiz edilmiş ve çalışma alanına ait toprakların elektriksel iletkenlik (EC) haritası oluşturulmuştur. Yer kontrol verileri kullanılarak uydu verileri sınıflandırılmış ve çalışma alanının arazi kullanım sınıfları belirlenmiştir. Toprak tuzluluğunun ürün verimi üzerindeki etkisini tahmin etmek için EC, arazi kullanımı, toprak ve parsel haritaları birleştirilerek GIS ortamında analiz edilmiştir. Çalışma sonucunda, 13.4 dS/m'ye kadar yükselen EC değerleri pamuk ve buğday veriminde sırası ile % 29.6 ve % 35.4 oranında azalmaya neden olmuştur. Pamuk ve buğdayın tolerans sınırı üzerindeki tuzluluk değerleri doğrusal bir ürün azalmasına neden olmuştur. Çalışma sonuçları, pamuk ve buğday bitkisi üretiminde görüldüğü gibi, tuzluluk etkisinin tahmininde uzaktan algılama ve coğrafi bilgi sistemlerinin uygun bir teknik olduğunu göstermiştir.

Anahtar Sözcükler: Uzaktan Algılama, GIS, nispi ürün, ürün verimi, tuzluluk, EC

Introduction

Soil salinity problems generally occur in arid and semi-arid regions and reduce crop production at different levels. Salinity is also a major limiting factor for crop yield in poorly drained soils (Mikati, 1997; Gafni and Zohar, 2001; Rogers, 2002; Patel et al., 2002).

In some areas of the world where salinity is a major problem, it is rather difficult to monitor the required ground information in the areas affected by salinity (Gates et al., 2002). Multitemporal analysis might be effective in detecting salt dynamics in a certain region and assessing the degree of damage on both crops and yield.

The use of satellite imagery for monitoring salinity has proved feasible in large areas where salinity is already a serious problem (Su et al., 1989; Metternicht, 2001). Despite some criticisms, remote sensing techniques have been shown to be a rapid and useful tool in monitoring and predicting salt-related crop productivity problems (Rahman et al., 1994; Alsaifi and Quari, 1996; White, 1997). The integration of satellite imagery and

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geographic information system (GIS) has enabled new evaluation possibilities in agricultural areas.

Since dynamic crop simulation models are not perfect and have generally been developed and tested for application at the scale of homogeneous plots, there is an issue associated with the up-scaling of model outputs linked with GIS. Decision makers usually need information at broader spatial scales where the assumption of a homogeneous environment does not hold and at higher system levels where different constraints operate (Hansen and Jones, 2000).

This study was conducted on the soils of Arıcan village, located on Harran Plain, where the salinity problem is widespread, and the effects of salinity were evaluated on crop yield by using satellite imagery and GIS. To the best of our knowledge, this study is the first to be performed on Harran Plain by using satellite imagery and GIS to collect information about the effects of salinity on crop production.

Materials and Methods

This research was carried out in Arıcan village, located in the southeastern part of Harran Plain (Figure 1).

The research area is a semi-arid region with an average annual rainfall of about 300 mm and annual evaporation of about 2000 mm measured from a bare soil surface. The research area has a shallow water table, and shows a salt accumulation in the surface and sub-surface horizons.

The soil map of the study area, (scale 1:25.000) was digitized into polygons of different types of soils, which were linked to an attribute database containing soil characteristics. The soil vector layer was then rasterized and resampled to a 25 m pixel to enable its geographical link to the raster image.

In order to evaluate crop yield, the parcel map of the research field (scale 1:5.000) was digitized and converted to a UTM raster layer using ArcView and ERDAS software.

The IRS LISS III imagery, acquired in July 2000, was used to determine types of land use. The image was geometrically corrected by identifying ground control points in the original image and on the reference maps. Supervised classification was executed to determine land use type using ground truth information. Ground reference maps, topographic maps and hard copies of the satellite images were used to identify the relevant land use pattern in the study area.

Soil samples collected from all soil series in the study area were analyzed and added to a tabular database to form an electrical conductivity (EC) map.

The land use map was combined with the EC map to evaluate the effect of salinity on yield production. Then the parcel map was overlapped to determine the effect of salinity on crop yield production at field level.

The response of a crop to salinity can be represented by the following equation (Maas and Hoffman, 1977):

$$y/Ym = 100\text{-}B(ECe\text{-}A) \qquad [1]$$

where

y/Ym = relative yield (%).

Ym = maximum yield obtained with good water.

ECe = electrical conductivity of a saturated soil paste extract (dS m^{-1}).

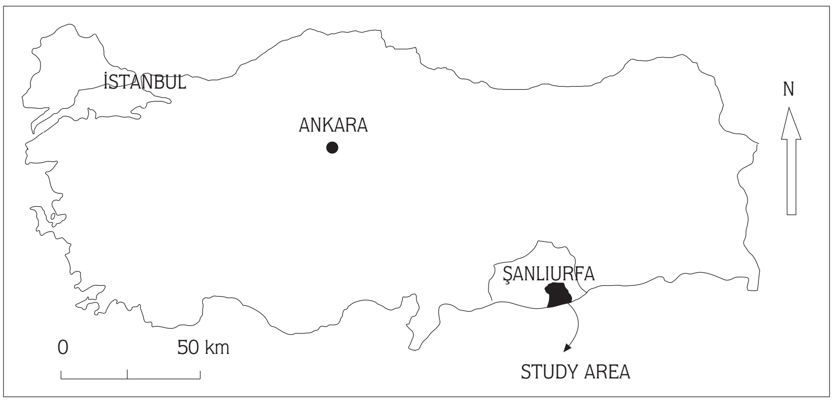

Figure 1. Location of the study area.

A = salinity threshold (dS m^{-1}) beyond which there is a yield decrease.

B = percent yield decrease per unit increase in salinity (dS m^{-1}).

According to Maas and Hoffman (1977), the value of the threshold A is 7.7 dS m^{-1} for cotton and 6.6 dS m^{-1} for wheat, and the yield decrease B is 5.2 % per dS m^{-1}.

Results and Discussion

The GIS and remote sensing techniques were used for determining the effects of salinity on crop yield on Harran Plain, located in an arid and semi-arid region.

Following the introduction of intensive irrigation on the Harran Plain, a significant increase in salinity has been noted and this has been attributed to the shallow groundwater level (Çullu et al., 2002), leading to considerable reductions in crop production (Çullu et al., 2000).

In order to determine the effect of salinity on crop yield, the soil EC map was prepared and integrated onto the parcels using the GIS (Figure 2).

Figure 2 shows the three levels of salinity, slight (4 dS m^{-1}), moderate (9.2 dS m^{-1}) and strong (13.4 dS m^{-1}), determined as the parcel base. These results were used to estimate the effect of salinity on crop yield by using equation [1].

The integration of crop models with a geographic information system increases the scope of applicability of models for regional planning and policy analysis (Hartkamp et al, 1999).

After collecting ground truth information, the supervised classification was executed and the land use types, such as cotton, wheat and bare soil, were determined (Figure 3).

The classification accuracy of cotton, wheat and bare soil were 96.8 %, 94.8 and 95.5 respectively.

The integration of the EC map with the classified image revealed that the main land use type occurs at different EC levels. The results showed that cotton was the dominant crop with 406 ha coverage and wheat was the second most important crop, covering an area of 64 ha. The results indicated that the major cotton and wheat areas had a high level of salinity (13.4 dS m^{-1}) (Table 1).

As expected, above the threshold levels high EC values in the soil resulted in a decrease in the yield of cotton and wheat. The DİE (1998) reported that average cotton and wheat production under non saline conditions were 3.5 t and 2 t ha^{-1}, respectively.

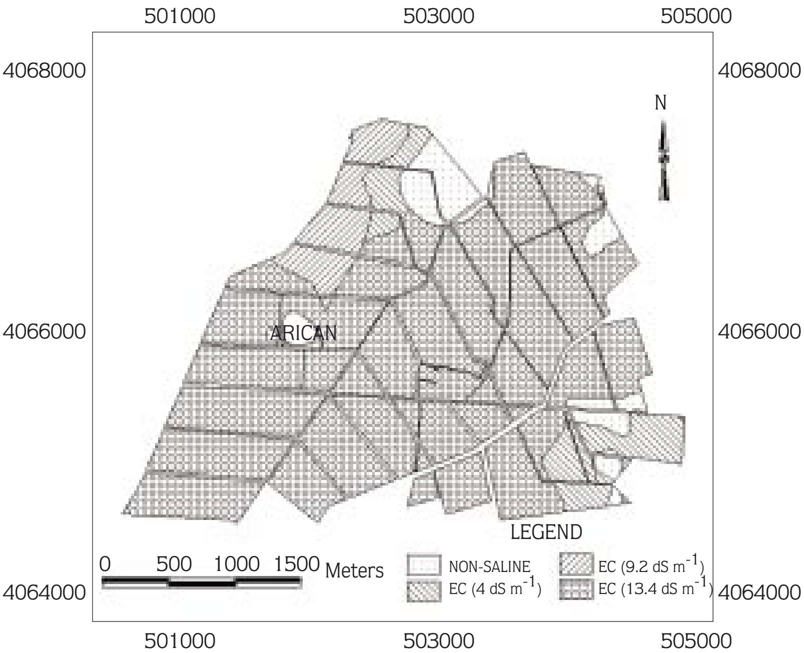

Figure 2. EC map of the research area combined with parcels.

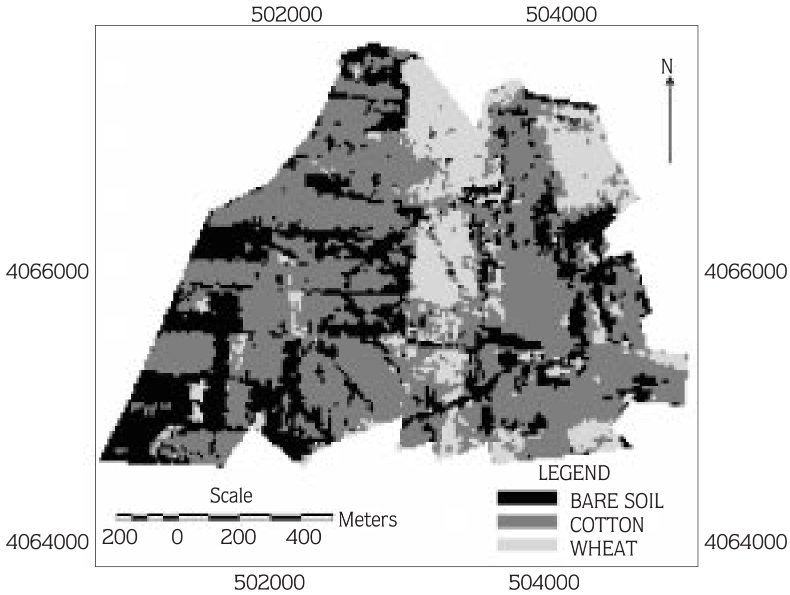

Figure 3. Land use type determined by supervised classification.

Table 1. Distribution of land use types according to EC values.

Land Use Type	Total Area (ha)	Classified Area (ha) for EC 4 (dS m^{-1})	Classified Area (ha) for EC 9.2 (dS m^{-1})	Classified Area (ha) for EC 13.4 (dS m^{-1})
Cotton	406	42	23	341
Wheat	64	6	1	57
Bare Soil	113	5	3	105

Table 2. Relative yield and total crop production in relation to EC values.

Land Use Type	Relative Yield Reduction (%)	Total Yield Reduction (ton) for EC 9.2 (dS m^{-1})	Relative Yield Reduction (%) for EC 9.2 (dS m^{-1})	Total Yield Reduction (ton) for EC 13.4 (dS m^{-1})	Total Yield Reduction (ton) for EC 13.4 (dS m^{-1})	r*
Cotton	7.8	6.3	29.6	353.3	359.5	-0.947
Wheat	13.5	0.3	35.4	40.4	40.7	-0.978

* Correlation coefficient between EC and total yield reduction for cotton and wheat.

The EC level of 9.2 dS m^{-1} decreased the total cotton and wheat yields by 7.8 % and 13.5 %, respectively. Total yield reductions were 29.6 % for cotton and 35.4 % for wheat at the EC level of 13.4 dS m^{-1}. Increasing EC levels from 9.2 to 13.4 dS m^{-1} caused a loss of 359.5 t in the total cotton planted area and of 40.7 t for the total wheat planted area (Table 2).

EC values above the thresholds for cotton and wheat caused decreases in relative yields. At EC levels of 9.2 dS m^{-1} and 13.4 dS m^{-1}, relative yields were 92.2 % and 70.4 % for cotton and 86.5 % and 64.6 % for wheat, respectively. This clearly indicates a critical influence of EC values on crop yield.

The correlation between EC and total yield reduction was significant: -0.947 and –0.978 for cotton and wheat, respectively (Table 2).

Such remarkable effects of soil salinity have been repeatedly reported by Ben-Hur et al. (2001), Daniels et al. (2001), Phogat et al. (2001) and Yang et al. (2002).

The effects of salinity at high EC values were found to be more dramatic for wheat than for cotton.

Cotton is known to be relatively salt tolerant (Ashraf, 2002). There is, however, a substantial variation in tolerance to salinity between cotton cultivars (Choundhary et al., 2001; Ashraf, 2002).

When the salinity map is drawn and the actual land use type determined for a particular area, it is possible to estimate the effect of salinity variations on the relative yield of targeted crops by using remote sensing and GIS techniques.

Conclusion

Accurate and reliable information at parcel level is needed to estimate the yield and to achieve effective planning, especially under adverse soil conditions, like soil salinity.

The relative yield reduction caused by salinity was higher in wheat than in cotton, increase in EC values from 9.2 dS m^{-1} to 13.4 dS m^{-1} decreased cotton and wheat yields by 29.6 % and 35.4 %, respectively.

The results of the present research also showed that the integration of GIS and remotely sensed data can be a useful tool for monitoring the effect of salinity on crop yield. These data can be used reliably by decision makers and land planners in determining priority areas for the implementation of salinity action plans.

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