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Sustainable production zoning for agroclimatic classification using GIS and remote sensing

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Abstract—Agriculture is a primary productivity sector which is highly dependent on environmental conditions. The agroclimatic potential of agricultural areas has to be assessed in order to achieve sustainable and efficient use of natural resources in combination with production maximization. Temperature and rainfall, in terms of quantity and spatiotemporal variability, are variables which determine the type of crops suitable to a given location. Rainfall variable can also be interpreted as availability of sufficient water required for production of given crops. These variables, in combination with soil type and geomorphology, also determine areas where high levels of production are appropriate, avoiding the threat of degrading the natural resources. In the current work, zones indicating water availability are combined with topographic features and soil types in order to identify areas for sustainable production. Firstly, aridity index (AI) and vegetation health index (VHI) are used in order to define zones adequate for sustainable farming according to water limitations. As crop growth is affected by water supply, these zones are named water limited growth environment (WLGE) zones. AI and VHI are computed on monthly time step for twenty hydrological years, from October 1981 to September 2001. VHI is derived from NOAA/AVHRR data, while in AI computations both satellite and conventional field data are used. Then, WLGE zones are combined with soil maps and a digital elevation model (DEM) of the area under investigation in order to define zones appropriate for sustainable production. The study area is the aquatic district of Thessaly, located in Central Greece. The current application has resulted in the definition of sustainable production zones by means of parallelepiped supervised classification using the two indices, soil maps and DEM. These zones can be further used for agroclimatic classification.

Key-words: sustainable production, WLGE, VHI, AI, remote sensing, GIS

1. Introduction

The climate is among the most important factors that determine the agricultural potentialities of a region and the suitability of a region for a specific crop, whereas the yield is determined by weather conditions (*Pereira*, 1982). Since agriculture is highly dependent on environmental conditions, a quantitative understanding of the climate of a region is essential for developing improved farming systems (*Reddy*, 1983).

Temperature and rainfall, in terms of quantity and spatiotemporal variability, are variables which determine the type of crops suitable to a given location (*Mavi* and *Tupper*, 2004). Even thought crop production depends on every environmental condition, almost all agroclimatic classifications take into account these variables. These climatic parameters in combination with soil type and geomorphology can determine areas where high levels of production are appropriate, avoiding the threat of degrading the natural resources (*Mavi* and *Tupper*, 2004).

Crop production requires the availability of sufficient water. In irrigated and rainfed agriculture, production is often constrained by water limitations during the growing season. Amount and distribution of rain during the growing season and supplemental irrigation along with soil characteristics and evapotranspiration losses determine the temporal pattern of water availability for plant use and the ensuing crop biomass and economic yield (*Arora* and *Gajri*, 1998).

The amount of rain needed for the production of a crop differs from region to region, mainly due to the decreasing "effectiveness" of rainfall in order to maintain plant growth due to the increasing evaporation (*Tow*, 1991). Effective rainfall is related to the moisture available in the plant's root zone, allowing the plant to germinate, emerge, and maintain its growth (*Mavi* and *Tupper*, 2004). There are many climatic and agroclimatic classifications seeking to describe the moisture conditions of crops (e.g. *Thornwaite*, 1948; *Reddy*, 1983). These classifications vary in complexity, ranging from the use of one parameter to methods incorporating a number of parameters. Most of these agroclimatic classifications used rainfall and potential evapotranspiration in order to delimit the growth environment of crops (*Badini et al.*, 1997).

Badini et al. (1997) investigated the water limited growth environment (WLGE) for millet cultivation in Burkina Faso, where rainfed production is a major source of food and income. They used aridity index (AI) and crop water stress index (CWSI) for defining such environments. AI incorporates rainfall and potential evapotranspiration. CWSI integrates all factors affecting water availability for crop growth but has the limitation of being crop specific.

One major application of remote sensing to agriculture is crop monitoring and assessment of vegetative stress. Satellite derived indices have been extensively used for identifying stress periods in crops or generally vegetation (*Steven* and *Jaggard*, 1995). In most cases the identification of vegetative stress is being held by the use of vegetation indices (*Domenikiotis et al.*, 2002; *Kogan*, 1995, 2001, 2002; *Tsiros et al.*, 2004).

Kogan (2001) proposed the vegetation health index (VHI) for monitoring the impact of weather to vegetation, and to use it for agricultural drought monitoring and mapping. Agricultural droughts reflect vegetation stress caused by the adverse climatic and hydrologic factors (*Bhuiyan et al.*, 2006; *Kogan*, 2002). VHI is a combination of vegetation condition index (VCI) and temperature condition index (TCI) derived by NOAA/AVHRR satellite data. In Greece, VCI and TCI have proven to be useful tools for the detection of agricultural drought (*Domenikiotis et al.*, 2002; *Tsiros et al.*, 2004).

In Greece, *Tsiros et al.* (2008) classified the WLGE using satellite derived VHI and AI. VHI represents overall vegetation health (moisture and thermal conditions) (*Kogan*, 2001) and is suitable for identification of vegetative stress, especially in cases where no specific crop is examined. AI represents climatic aridity and is used to determine the adequacy of rainfall in satisfying the water needs of crops.

The first objective of this study is to define a general methodology (not crop specific) for identifying WLGE using GIS and remote sensing. Therefore, the two indices are used to define zones adequate for agricultural use according to water limitations (WLGE zones). The second objective is to identify sustainable production zones in terms of water sufficiency, fertility (appropriate or not for agricultural use), desertification vulnerability, and altitude restrictions. Thus, WLGE zones are combined with soil maps and a digital elevation model (DEM). In order to apply new management techniques, transfer new technologies and plan alternative crops according to the bio-physical characteristics of each region, a quantitative understanding of the relationships among crop, climate, and soil are needed (*Badini et al.*, 1997). Defining areas of sustainable crop production is a major step for identifying agroclimatic zones, considering environmental limitations and the sustainable use of natural resources.

2. Study area and preprocessing

The study area is the geographical region of Thessaly (*Fig. 1*) and specifically the water district of Thessaly, located in Central Greece. Thessaly is a region of plains surrounded by mountains. The ridges of these mountains are the borders of the water district of Thessaly. Having higher percent of flatlands than any other district in Greece, 38.7% of the population is occupied in the primary productivity sector and thus, Thessaly is a major supplier of agricultural products.

The increase in agricultural activities and the intensive type of agricultural practices applied in Thessaly, resulted in an insufficient use of natural resources. Low and irregular amount of rain during the summer period lead to regional drought events which in combination with the oversized pumping and the bad management of irrigation water (old irrigation practices and network, increased water losses, more amount of irrigation water than needed) led to degradation of water resources and lowering of the ground water table. Thus, there is a necessity for identifying areas which are capable to fulfill crop water needs without aggravating the current conditions.

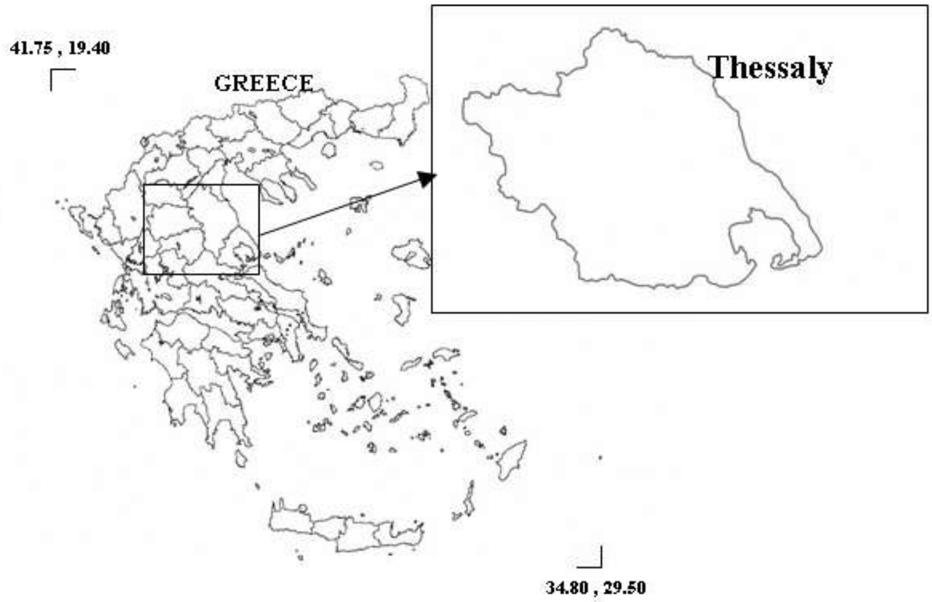


Fig. 1. Location of the study area.

The data base consists of NOAA/AVHRR satellite data and conventional data for 20 hydrological years, from October 1981 to September 2001. In specific:

- Normalized difference vegetation index (NDVI), channel 4 (CH4) and channel 5 (CH5) brightness temperature (BT) ten-day composite satellite images (8 × 8 km spatial resolution).
- Monthly rainfall maps with grid cell size 50 × 50 km (*ISPRA*, 2006).
- Mean monthly air temperature measurements from Larissa meteorological station (National Meteorological Service, NMS).
- Soil map of the study area (*Yassoglou*, 2004).
- Digital elevation model derived from 100m contours.

All satellite data are obtained on-line by NASA archives. NDVI maps are ten-day maximum value composite (MVC) images. CH4 and CH5 images are converted to BT using the equation provided by the info file of the data set. Using the ten-day images, NDVI and BT images are composed over a monthly period using the MVC and mean pixel value, respectively. Missing data due to cloud cover or sensor’s technical problems are completed using monthly climatic values derived from the images of the time series which presented no blunders. Rainfall maps were produced using the data of ISPRA European database (ISPRA, 2006). The subset satellite images and rainfall maps cover the entire area of Greece. After all computations have been carried out, the area under investigation is isolated.

Before using NDVI and BT images, fluctuations induced by noise must be removed. The combination of the filtering and the MVC can significantly reduce the noise from residual clouds, fluctuating transparency of the atmosphere, target/sensor geometry, and satellite orbital drift (*Goward et al*., 1991). Other noise can be related to processing, data errors, or simple random noise (*Kogan*, 1995).

In the current study, a "4253 compound twice" median filter (*Van Dijk et al*., 1987) is applied to the NDVI images, whereas a "conditional" statistical mean spatial filter (window size ranging from 3 × 3 to 7 × 7, according to image needs) has been used for smoothing the BT series (*Tsiros et al*., 2008). The BT series presented continuous spatial fluctuations, and thus, a spatial filter (statistical mean) has been preferred for smoothing channel 4 and channel 5 BTs. "Conditional" means that the filter is applied only to the pixels that presented errors.

3. *Methodology*

Remote sensing is a useful tool to analyze the vegetation dynamic. Several studies have shown that inter-annual differences in vegetation parameters are mainly driven by water availability (*Al-Bakri* and *Taylor*, 2003; *Weiss et al.*, 2004). Thus, AI and VHI are used in order to define zones adequate for sustainable farming according to water limitations (*Tsiros et al.*, 2008). As crop growth is affected by water supply, these zones are named water limited growth environment zones (*Badini et al.*, 1997). Furthermore, these zones are combined with soil maps and a DEM of the area under investigation in order to define zones appropriate for sustainable crop production due to water, soil, and altitude restrictions.

3.1. Water limited growth environment

The first index used to identify WLGE is VHI. VHI is a combination of VCI and TCI derived by a long term NDVI and channel 4 images from NOAA/AVHRR satellite. NDVI, is obtained by combining the channels 1 and 2, the visible and near infrared, respectively, of NOAA/AVHRR. NDVI is a quick and efficient way for the estimation of vivid vegetation. NDVI is indicative of the level of photosynthetic activity in the vegetation monitored, reflecting whether the vegetation is stressed or not. After stressed conditions, significant reduction in NDVI of the field is expected.

VCI and *TCI* characterize the moisture and thermal conditions of vegetation, respectively (*Bhuiyan et al.*, 2006; *Kogan*, 1995, 2001, 2002) and are given by the equations:

$$VCI = 100 \cdot \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}}, \quad (1)$$

$$TCI = 100 \cdot \frac{BT_{\max} - BT}{BT_{\max} - BT_{\min}}, \quad (2)$$

where $NDVI$, $NDVI_{\max}$, and $NDVI_{\min}$ are the smoothed ten-day normalized difference vegetation index, its multi-year maximum and minimum, respectively; BT, $BT_{\max}$, and $BT_{\min}$ are the smoothed ten-day radiant temperature, its multi-year maximum and minimum, respectively, for each pixel, in a given area. Thermal conditions are especially important when moisture shortage is accompanied by high temperature, increasing agricultural's drought severity, having direct impact to vegetation's health. *VCI* and *TCI* vary from zero, for extremely unfavorable conditions, to 100, for optimal conditions. Thus, higher *VCI* and *TCI* values represent healthy and unstressed vegetation.

Both indices are based on the same concept. Maximum amount of vegetation is developed in years with optimal weather conditions, whereas minimum vegetation amount develops in years with extremely unfavorable weather (mostly dry and hot). Therefore, the absolute maximum and minimum values of NDVI and BT, calculated from several years, contain the extreme weather events (drought and no drought conditions). The resulted maximum and minimum values can be used as criteria for quantifying the environmental potential of a region (*Kogan*, 1995).

VHI represents overall vegetation health (*Kogan*, 2001). The five classes of VHI that represent agricultural drought are illustrated in *Table 1* (*Bhuiyan et al.*, 2006; *Kogan*, 2001). VHI is expressed by the following equation:

$$VHI = 0.5 \cdot (VCI) + 0.5 \cdot (TCI). \quad (3)$$

In *VHI* computation, an equal weight has been assumed for both *VCI* and *TCI*, since moisture and temperature contribution during the vegetation cycle is currently not known (*Kogan*, 2001).

Table 1. VHI drought classification schemes (*Kogan*, 2001)

VHI values	**Agricultural drought classes**
<10	Extreme drought
<20	Severe drought
<30	Moderate drought
<40	Mild drought
>40	No drought

The other index used to identify WLGE zones is AI. AI is a function of the ratio of precipitation to potential evapotranspiration. The categories as they are defined by the values of AI are illustrated in *Table 2* (*UNESCO*, 1979). In this study, AI represents climatic aridity and is used to determine the adequacy of rainfall in satisfying the water needs of crops. The index is calculated on multi-year basis, using monthly values. The potential evapotraspiration is calculated with the use of Blaney-Criddle method (*Tsiros et al.*, 2008). The method estimates potential evapotranspiration (ET_p) using monthly air temperature data, the ratio of daytime hours (month/year), and a weighted crop coefficient (C). Regarding the weighted crop coefficient, 12 maps with grid cell size of 100 × 100 m (one for each month) have been utilized. C values are defined according to land use provided by CORINE 2001 database.

Table 2. Characterization of an area according to aridity index, AI (*UNESCO*, 1979)

Category	**AI**
Extremely dry	<0.03
Dry	0.03 – 0.20
Semi-dry	0.20 – 0.50
Semi-wet	0.50 – 0.75
Wet	>0.75

In ET_p calculations, land surface temperature (LST) is used instead of air temperature. The generation of LST maps is based on the “split-window” algorithm from *Becker* and *Li* (1990), which uses the differential absorption effects in channels 4 and 5 for correcting atmospheric attenuation mainly caused by water vapour absorption. For estimating surface emissivity, the relationship given by *Van de Griend* and *Owe* (1993) is applied.

In order to avoid over-estimating ET_p, LST is converted to air temperature using a linear empirical relationship. The relationship has been derived by applying a regression analysis to the LST and air temperature data of the time series ($R^2 = 0.84$). Results are depicted in *Fig. 2*.

Since both indices have been computed, two maps are created. From the VHI images a final map is obtained using the frequency of occurrence of agricultural drought events. The derived map is combined with the climatic aridity map and led to the definition of WLGE zones. The generalized thematic classification scheme is illustrated in *Table 3*.

3.2. Soil map and DEM

Overlapping WLGE zones, a soil map, and a DEM of the study area has led to the definition of regions where crop production is sustainable and agriculture is the best suited agronomic use. Soil types are digitized according to fertility (appropriate or not for sustainable agricultural use) and desertification vulnerability. The sustainable agronomic use and the desertification risk according to soil category are adopted by *Yassoglou* (2004). Soil types are grouped into three classes during the digitization. Soils appropriate for agricultural use, controlled agricultural use, and no agricultural use. The classification pattern is illustrated in *Table 4*. Finally, the digitized vector map is converted to raster (grid) with cell size of 100 × 100 m.

As mentioned earlier, the DEM is constructed using 100 m interval contours. Three major crop growth zones are selected according to altitude limitations (*Danalatos*, 2007). The first, ranging from zero to 600 m, is appropriate for almost all crops. The second, ranging from 600 m to 900 m is appropriate for non-tropic crops and fruit trees (maize, winter wheat, apple trees, chestnuts, etc.). The last one, having altitude values higher than 900 m is not appropriate for crops. Again, the derived zones are converted to raster (grid) with cell size of 100 × 100 m.

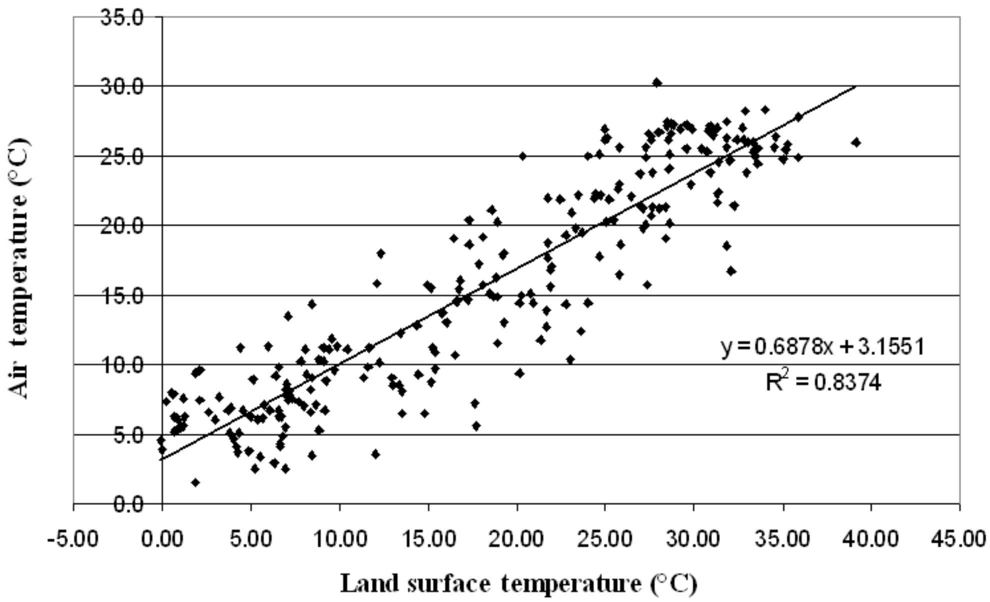


Fig. 2. Application of linear regression analysis to land surface temperature and air temperature.

Table 3. WLGE generalized classification scheme (*Tsiros et al.*, 2008)

Agricultural drought classes	**Aridity classes**	**WLGE classes**
Extreme drought	Extremely dry	Limited Environment
Severe drought	Dry	
Moderate drought	Semi-dry	Partially limited Environment
Mild drought	Semi-wet	
No drought	Wet	No limitations

Table 4. Classification scheme of soil types according to sustainable use and desertification vulnerability

Class name	**Sustainable agronomic uses**	**Desertification vulnerability**	**Soil types category**
No agricultural use	Wild nature, Forest Controlled pasture	Very high High	Rock outcrops Leptosols, Regosols (low quality) Cambisols (medium-low quality)
Controlled agricultural use	Controlled agriculture and pasture Forest	Medium	Regosols (medium quality) Cambisols (medium-high, high quality) Luvisols (medium quality)
Agricultural use	Agriculture	Low	Fluvisols, Vertisols, Luvisols (high quality)

3.3. Supervised classification

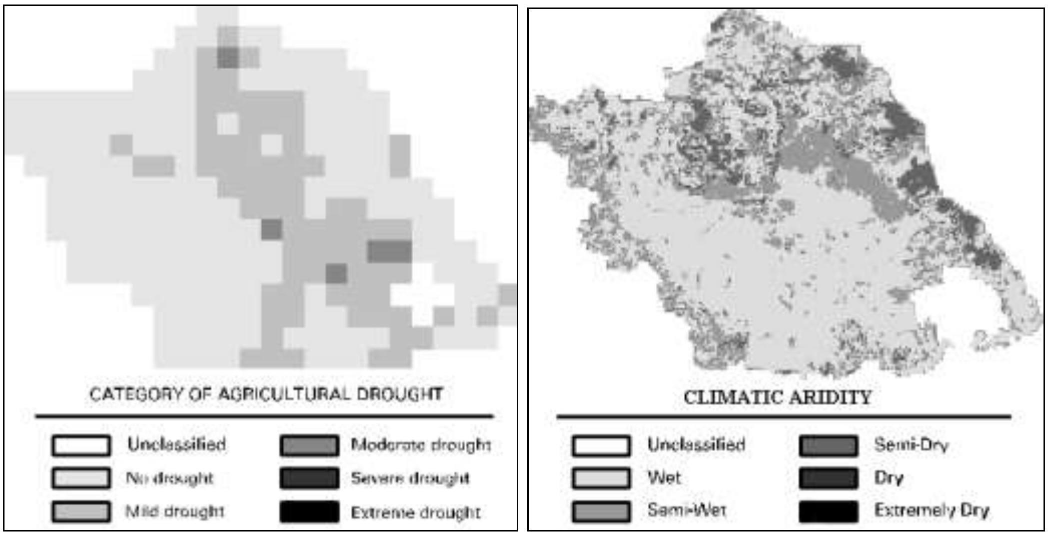
During the supervised classification, the parallelepiped technique is used in order to combine the WLGE zones, the soil map and the DEM and define the sustainable production zones. During the classification, the following rule pattern is used. Crop production is:

- "Unsustainable" in areas characterized by any of the "limiting" classes.
- "Sustainable under restrictions" when "partial limitations" regarding to WLGE or soil map or DEM (intermediate classes) exist.
- "Sustainable for non-tropic crops" in regions with "no limitations" and 600–900 m altitude range.
- "Sustainable" in areas with "no limitations" and altitude lower than 600 m.

4. Results and discussion

In this study, two satellite derived indices, VHI and AI are used to define areas where plant growth is limited by water availability. The calculation of the two indices resulted in the creation of two maps. One is characterizing areas according to the frequency of agricultural drought incidents (*Fig. 3a*) and the other is representing climatic aridity (*Fig. 3b*) for the period under consideration. *Figs. 3a* and *3b* show that there is no area in Thessaly water district where the climate regarding to AI is "dry" or "extremely dry", and "severe" and "extreme" drought events are frequent.

The definition of WLGE zones is the result of the combination of these two maps. The thematic classification scheme used is described as follows. A number has been assigned to every class of the two indices (five classes each). Number one corresponds to "wet" and "no drought" classes, grading the sequence up to five, which corresponds to "extremely dry" and "extreme drought" classes. By adding those numbers, three categories are utilized to delimit WLGE zones: (i) "limited" (values from 7 to 10) and (ii) "partially limited" (values from 3 to 6) growth environment, and (iii) the class where "no limitations" (values equal to two) exist according to water availability. The map of WLGE zones is presented in *Fig. 4*.



(a) (b)

Fig. 3. (a) Agricultural drought map of Thessaly water district derived using incidents frequency, (b) climatic aridity map of Thessaly water district.

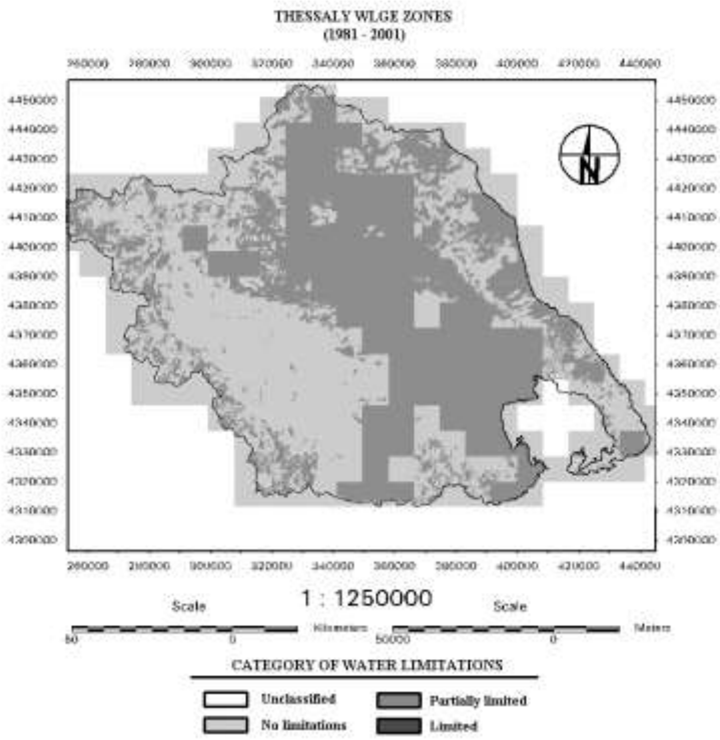
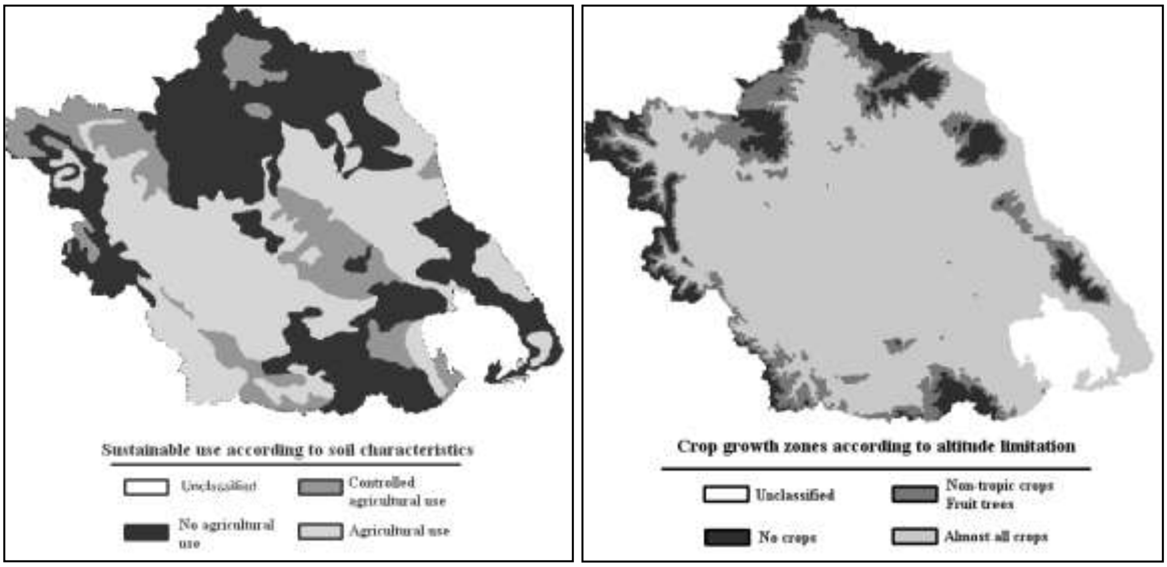


Fig. 4. Water limited growth environment zones of the water district of Thessaly.

Fig. 4 indicates that there is no area in Thessaly water district where plant growth is prohibited by water availability. The definition of "limited" growth environment indicates areas where moisture and rainfall cannot satisfy the water needs of crops or even a part of them. In order to satisfy crop requirements in those areas, large quantities of water supply from irrigation are required, leading to unsustainable use of water resources and increase of the cost of the final product. Areas of "partially limited" growth environment due to water availability need smaller amount of irrigation, whereas areas with "no limitations" even smaller. In such areas, a more effective use of water resources is being held, since a major part of crop water needs is supplied by rainfall and existing moisture conditions.

The combination of the WLGE zones, soil maps, and DEM resulted in the definition of sustainable production zones by means of parallelepiped supervised classification. The zones of sustainable use according to soil characteristics and the altitude based crop growth zones in Thessaly are depicted in *Figs. 5a* and *5b*, respectively, whereas the derived map of the sustainable production zones is presented in *Fig. 6*.



(a) (b)

Fig. 5. (a) Zones of sustainable use according to soil characteristics in Thessaly, (b) altitude based crop growth zones of Thessaly water district.

Fig. 6 shows that in the 35% of Thessaly water district agriculture is not a sustainable due to water, altitude, or soil limitations. The term "sustainable under restrictions" refers to the cultivation of crops that do not need large quantities as "input" regarding irrigation and fertilizers. Also, "sustainable under restrictions" indicates that the type of cultivation preferred to those areas is extensive and not intensive. Further work has to be done in order to define the type of crops and cultivation techniques applied to those areas. The sustainable production areas for non-tropic crops have small spatial coverage, because they are delimited by the relatively high altitudes. Lastly, sustainable production zones cover about 25% of Thessaly indicating that those areas of the water district are suitable for any agricultural use. But, in order to obtain sustainability, farming management practices such as crop rotation, use of crop cover, and combination with livestock grazing out of the growing season are essential. Most of the times, monocultures are not sustainable systems.

The main advantage of the methodology is that it uses satellite and raster data, providing continuous spatial and temporal information. In this way there are no fuzzy borders regarding the derived zones. Instead, methods that use conventional data are lacking the above advantages. But, despite the advantages, it is essential that the satellite data are calibrated and preprocessed properly before they are used as input data in any methodology. Lastly, another advantage of using these indices is that they are not crop specific.

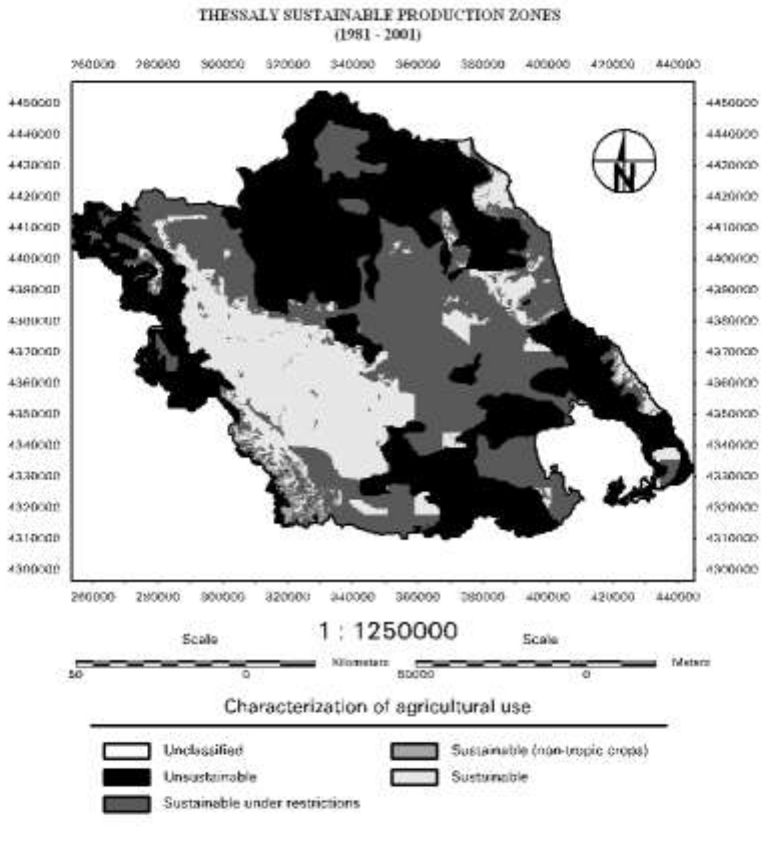


Fig. 6. Sustainable production zones of Thessaly water district.

5. Conclusions

The results of the current application justify the use of AI and VHI. Using VHI, areas frequently affected by agricultural drought are identified and excluded. The combination of the frequency of occurrence of such extreme events along with climatic aridity is useful for identifying areas unsuitable for crop production due to water availability. Such areas must be excluded from any sustainable management plan.

Thus, WLGE zones are important since they delineate areas where plant growth is limited by water availability. Moreover, the use of soil maps and DEMs excludes areas unsuitable for agricultural activities. Thus, the combination of WLGE zones along with soil maps and DEMs can be used to identify sustainable production zones. Such zones are essential in developing any sustainable development/farming plan, since they can be combined with crop specific agroclimatic indices in order to obtain agroclimatic zones.

The innovation of the proposed methodology consists of the joint use of the above described steps, as well as the classification of areas escalating the suitability of agricultural activities. Lastly, the methodology is not crop specific and has the advantage of providing total spatial coverage of the area under investigation.

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