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Growth and biomass productivity of kenaf (*Hibiscus cannabinus*, L.) under different agricultural inputs and management practices in central Greece

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ABSTRACT

The growth and biomass productivity of kenaf (*Hibiscus cannabinus*, L.) cultivars Tainung 2 and Everglades 41 were determined under three irrigation applications (low: 25%, moderate: 50% and fully: 100% of maximum evapotranspiration; ETm), four nitrogen dressings (0, 50, 100 and 150 kg ha^{-1}), two sowing dates, and two plant densities (20 and 30 pl m^{-2}) in two field experiments carried out on an representative aquic soil of western Thessaly plain (central Greece), in the period 2003–2005.

The results demonstrated a paramount effect of sowing time (and thus the availability of the vegetative growing period) on crop growth and biomass productivity; delayed sowings (after mid-May) may reduce biomass production by 38%.

Irrigation water had a significant effect ($P < 0.05$) on growth indices and biomass productivity fluctuating upon flowering from 15.1 to 18.5 and to 20.3 t ha^{-1} (3-year average values) for the low, moderate and fully irrigated plants, respectively. Stems are the economic yield comprising about 87% of the total biomass in all cases. The relatively small effect of 50% irrigation to biomass production was attributed to the increased soil moisture status of the studied (aquic) soil. Contrarily, N-fertilization in the studied range did not affect significantly growth and productivity due the high fertility status of the soil, while plant population in the study range had a minor effect ($P > 0.05$) on biomass accumulation. Cultivars performed similar growth rates (no significant differences), which under full water and nitrogen inputs reached maximum growth rates of 180–220 kg ha^{-1} day^{-1} which may serve as reference for the assessment of crop performance under production situations at hierarchically lower input and management levels for central Greek conditions.

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1. Introduction

Kenaf (*Hibiscus cannabinus* L.) is a warm-season, annual crop with a C$_3$ photosynthetic pathway, achieving particularly attention in the last decade as an alternative (multi-purpose) crop for energy and paper pulp production. Although tropical in origin, kenaf cultivars are well adapted to a wide geographical and climatic range (Meints and Smith, 2003). Kenaf was introduced in Mediterranean region (Italy) in early 1950s mainly for the production of textile fibers, while after 1980s the crop was studied mainly for paper pulp production (Belocchi et al., 1998). After 2003, kenaf has been examined for its possible uses in bio-energy sector (Alexopoulou et al., 2004). Kenaf has been reported to be 3–5 times more productive per unit area than pulpwood trees, producing pulp with quality equal or superior to that of many wood species (Francois et al., 1992). The commercial product of the crop is the stems, which contain two distinct fibers: the long fibers that produce high-quality paper; and the shorter fibers giving lower quality paper. Kenaf can be used also as bedding materials, as substrate mixtures, as building material and as forage for livestock (McMillin et al., 1998; Nielsen, 2004; Webber, 1993; Webber and Bledsoe, 2002).

The prospects of kenaf becoming an alternative crop for inclusion into the existed rotation schemes in Greece, is dependent on the possibility to obtain large biomass amounts at low production cost (Quaranta et al., 2000). To achieve this, agronomical and cultivation parameters such as water and nitrogen input requirements, appropriate sowing date, cultivar selection and planting density, which are among the main determinates of plant growth, should be determined. Considerable information on kenaf agronomy and biomass productivity has been reported from Australia (Carberry et al., 1992; Carberry and Muchow, 1992; Muchow, 1992; Muchow and Carberry, 1993; Wood and Muchow, 1980; Wood et al., 1983) and USA (Banuelos et al., 2002; Bhardwaj et al., 2005; McMillin et al., 1998; Meints and Smith, 2003; Nielsen, 2004; Webber, 1996; Webber and Bledsoe, 2002).

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Table 1
Phenological dates and water inputs during the growing seasons of kenaf.

Year	Date of sowing (JD)	Date of 50% emergence (JD)	Date of 50% flowering (JD)	Growing days (days)	Irrigation[a] applied (mm)	Rainfall[a] effective (mm)	A-pan[a] season (mm)
Exp-1							
2003 (early)	140	146	290	144	348	132	875
2003 (late)	165	169	302	133	321	234	732
2004 (early)	153	158	294	136	492	175	830
2004 (late)	183	188	306	118	470	155	601
2005 (early)	96	105	282	177	540	99	1146
2005 (late)	154	158	292	134	455	12	827
Exp-2							
2003	140	146	286	140	348	132	866
2004	153	158	291	133	492	175	823
2005	102	115	276	161	540	99	1067

JD = Julian days.

[a] Period from 50% emergence to 50% flowering.

Many researchers highlighted the dominant effect of irrigation on kenaf yield. In Australia, Carberry and Muchow (1992) reported kenaf yields in the range 8.3–25.1 t ha^{-1} in response to irrigation application (50–1025 mm). Similarly, in USA Banuelos et al. (2002) and McMillin et al. (1998) found a strong response of several kenaf cultivars to irrigation application (350–1450 mm); with the kenaf cvs. Tainung 2 and Everglades 41 reached maximum yields of 23.4–25.8 t ha^{-1} under full water inputs. In a Mediterranean environment (Italy), recently, Patanè et al. (2007) reported kenaf yields from 8 to 24 t ha^{-1} in line to water restoration (0–100% of ETm). Apart from irrigation that has a clear positive effect, there is contrasting information on the impact of nutrient application on kenaf yields. Kipriotis et al. (2007), Manzanares et al. (1997) and Patanè et al. (2007), reported no effect of nitrogen application (range: 0–150 kg N ha^{-1}) on kenaf yield in different soils around Mediterranean region. In contrast, Bhangoo et al. (1986), Kuchindra et al. (2001), Muchow (1992) and Webber (1996) working at different soil-climatic conditions found a positive effect of nitrogen on kenaf yields, which were maximized with N-dressings in the range 86–224 kg N ha^{-1}.

Besides agricultural inputs; management practices are also very important in determining adaptability and biomass productivity. Appropriate sowing time is strongly related to temperature and according to Carberry and Abrecht (1990) a basal temperature of 10 °C should be satisfied prior to sowing. Usually crops were sowed at higher air temperatures to support early and uniformity crop emergence. On the other hand, kenaf is a photoperiod sensitive crop, where flowering is achieved below a critical photoperiodic level (Carberry et al., 1992; Gray et al., 2006). The last is a cultivar specific characteristic with the less sensitive or late maturing kenaf cultivars to be associated with higher yields. Indeed, in numerous experiments on cultivar adaptability and productivity in different locations it was found that cvs. Tainung 2 and Everglades 41 belong to late maturing group with yields to vary from 12.4 to 23.9 t ha^{-1} and a growing cycle of 130–180 days depending on latitude and sowing date (Alexopoulou et al., 2000; Banuelos et al., 2002; Belocchi et al., 1998; Kipriotis et al., 2007; Liu and Labuschagne, 2009; McMillin et al., 1998; Meints and Smith, 2003; Webber and Bledsoe, 2002). Additionally, planting density comprises another important management factor influencing biomass yield. However, kenaf compensates well across a wide range of plant populations (10–90 pl m^{-2}; Muchow, 1979), while it seems that a plant density of 18–37 pl m^{-2} may be desirable for maximizing stalk yield (Alexopoulou et al., 2000; Carberry and Muchow, 1992; Webber and Bledsoe, 2002).

However, these literature data require review since soil-climatic conditions are modified throughout different locations. For Greece, agronomic literature on kenaf is scarce. Considering that any assessment of land use performance needs to quantify the biophysical production potential followed by analyses of productivity at hierarchically lower levels of inputs and management practices, the focus of this paper is the determination of the growth rates and biomass productivity of kenaf in the western Thessaly Plain, central Greece. This area was chosen since Thessaly comprises the largest lowland formation and the country's centre of agricultural production. Due to its high fertility status and aquic properties, the study soil – representing extensive areas in the western Thessaly plain – may ensure optimum water availability upon modest irrigation inputs and finally maximum growth rates and productivity. Additionally, the reduction of this production potential will be further assessed for different irrigation application inputs (25, 50 and 100% of ETm), nitrogen fertilization application inputs (0, 50, 100 and 150 kg ha^{-1}), sowing times (early and late), cultivars (Tainung 2 and Everglade 41) and plant densities (20 and 30 pl m^{-2}). Such data are useful for cost/benefit projections for future cropping systems and crop rotations including kenaf in Greece and the Mediterranean region more generally.

The present work was conducted in the frame of the EU project Biokenaf – Biomass Production Chains and Growth Simulation Model for kenaf, whereas the study factors belong to a common experimental protocol. Actually, these datasets have been used to calibrate the simulation model (BioKenaF) for kenaf.

2. Materials and methods

2.1. Experimental site

A 3-year field experiment was carried out in the western part of the Thessaly lowland (Palamas, Karditsa, Greece) in 2003–2005. The experimental site is located at 39°25′N and 22°05′E, with an altitude of 107 m a.s.l. The soil at the site is a deep, calcareous (pH = 8–8.2), fertile (organic matter content of 1–1.5% at a depth of 50 cm), loam (sand 40–42%, silt 40–41%, clay 18–19%), developed in recent alluvial deposits and represents a large part of the West Thessaly Plain (central Greece). The soil is characterized by a moderately shallow groundwater table fluctuating from some 150 to 200 cm below the surface in May (artificial drainage) to deeper layers later in the summer, and is classified as Aquic Xerofluvent according to USDA (1975).

2.2. Field experiments and management

Two field experiments were carried out in the years 2003, 2004, and 2005. The dates of sowing and emergence for all experiments are summarized in Table 1. The date of flowering (50% of plants with one of more flowers) was also scored by regular inspection of 20 tagged plants in the inner rows of each plot

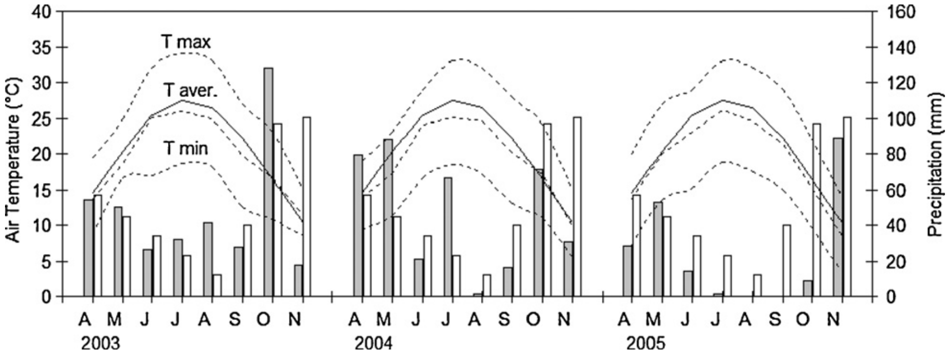

Fig. 1. Monthly means of maximum (T_{max}), minimum (T_{min}) and average ($T_{aver.}$) air temperature (°C; *x*-axis; dashed lines) and monthly total precipitation (mm; *y*-axis; grey columns) in the experimental site during 2003–2005 (April–November). Climatic air temperature (solid lines) and precipitation (open columns) are also illustrated (National Meteorological Service, 1973–2004).

(Table 1). The first experiment (Exp-1: management practices) was a randomized complete block design in three replications studying three factors: (i) sowing time (early and late), (ii) cultivar (Tainung 2: T2 and Everglades 41: E41), and (iii) plant density (20 and 30 pl m^{-2}). Sowing was done at rows 0.5 m apart with plant distances within the row of 0.10 and 0.05 m for low and high plant density, respectively. The second experiment (Exp-2: input application) was a 3 × 4 split–plot design in three replicates with the main plots comprising the three irrigation treatments [I_1 = 25% (low), I_2 = 50% (moderate), and I_3 = 100% of ETm (fully irrigated)], and the subplots comprising the four nitrogen dressings (N_0 = control, N_1 = 50 kg N ha^{-1}, N_2 = 100 kg N ha^{-1}, and N_3 = 150 kg N ha^{-1}). The cultivar T2 was used in this experiment at a planting density of 20 pl m^{-2}. Few days before sowing, all plots had received a basal dressing with 50 kg P and 50 kg K ensuring non-limited conditions, while N application occurred when the plant stands reached 40–50 cm in height.

Weather data such as incident solar radiation, air temperature, rainfall, relative humidity, wind speed and class-A pan evaporation rate, were recorded hourly on an automatic meteorological station (DL2, Delta-T, UK) which was installed at the experimental site. Drip irrigation was used to ensure the accuracy of the irrigation inputs. The irrigation was determined on the basis of the maximum available water content in the upper 60 cm of soil (effective rooting depth), using the following equation (Doorembos and Pruitt, 1977):

$$\mathrm{IRR} = (1 - \mathrm{DEPLF}) \times (\mathrm{SMFC} - \mathrm{SMWP}) \times \mathrm{RD} \times \mathrm{BD} \qquad (1)$$

where IRR = irrigation water amount (here equal to 55 mm); DEPLF = depletion fraction of available soil water (here equal to 0.50); SMFC = soil water content at field capacity (0.21 cm^3 water/g soil at −0.03 MPa); SMWP = soil water content at wilting point (0.08 cm^3 water/g soil at −1.5 MPa), RD = effective rooting depth (60 cm); BD = soil bulk density (1.42 g/cm^3). Irrigation was applied when the sum of daily maximum evapotranspiration (ETm) equals to IRR (usually 1 week period). ETm was calculated from daily class-A plan evaporation data and specific coefficients (Doorembos and Pruitt, 1977) as follows:

$$\mathrm{ETm} = \mathrm{Eo} \times \mathrm{Kp} \times \mathrm{Kc} \qquad (2)$$

where Eo = class-A evaporation pan rate in mm; Kp = pan-coefficient, equal to 0.80 (average relative humidity 40–70%, low wind speed); Kc = crop coefficient, ranging between 0.2 and 0.4 during the initial crop stages, 0.4–1.1 during crop development, equal to 1.1 during the mid-season and 1.1–0.7 during late season. The k_c values used in this study are very close to the values suggested from Quaranta et al. (2000) in a similar study on kenaf crop in Italy. The cumulative irrigation application rate (mm/season) for the 100% ETm treatment and the A-pan measures are also reported in Table 1.

2.3. *Measurements and calculations*

Growth and dry biomass productivity was monitored by means of subsequent destructive samplings (5–8 harvest per experiment) manually realized throughout the growing periods (2003–2005; see figures). In each sampling, 2 m^2 were harvested in the inner plot rows to avoid any border effect. Plant height was determined as the average for all harvested plants per plot. The plant material was weighted fresh and divided into the various plant components: leaf lamina, leaf petiole and stems. Storage organs were present only in the last harvest (October) and were incorporated into the stem biomass. Then the plant fractions were oven-dried at 90 °C until equal weights (3–4 days) and weighed again to determinate the respective dry weights., Dry sub-samples of the last harvest (for all experiments) were analyzed for nitrogen concentration (%) using the Kjeldahl method.

Before drying, leaf area (green leaf lamina) was measured using an automatic LI–COR model LI–3000A portable leaf area meter. Leaf area index (LAI m^2 green leaf m^{-2} ground) was determined as the product of green leaf dry weight (kg m^{-2} ground) times the specific leaf area (SLA in m^2 leaf kg^{-1}). Growing degree days (°C-days) were calculated using maximum and minimum daily air temperature records and a base temperature of 10 °C (Carberry and Abrecht, 1990). Growing degree days were computed from 50% of crop emergence and onwards.

All measured and derived data were subjected to analysis of variance (ANOVA), using GenStat, version 7.1 (PC/Windows XP) following the experimental designs. As test criterion for looking differences between means the $LSD_{0.05}$ was used (Steel and Torrie, 1982). Three years were not pooled for ANOVA because the sampling dates were not comparable among years.

3. Results and discussion

3.1. *Weather conditions*

In general the study area is characterized by a typical Mediterranean climate with hot, dry summers and cool, humid winters. Fig. 1 illustrates the mean air temperature and precipitation for all studied years (2003–2005). Mean air temperature reached a value of 25 °C (day-time: 29–30 °C, night-time: 20–22 °C) and maintained at this level during the summer time without considerable differences among the study years. Total precipitation from April to November was 337, 374 and 194 mm, respectively for 2003, 2004, 2005 (climatic average 301 mm). Data on effective precipitation during the growing period per season can be depicted from Table 1. In all experimental years, average relative humidity during summer was 61.31% (range: 41.1–87.4%) and average wind speed 1.23 m s^{-1}. It should be noticed that cotton

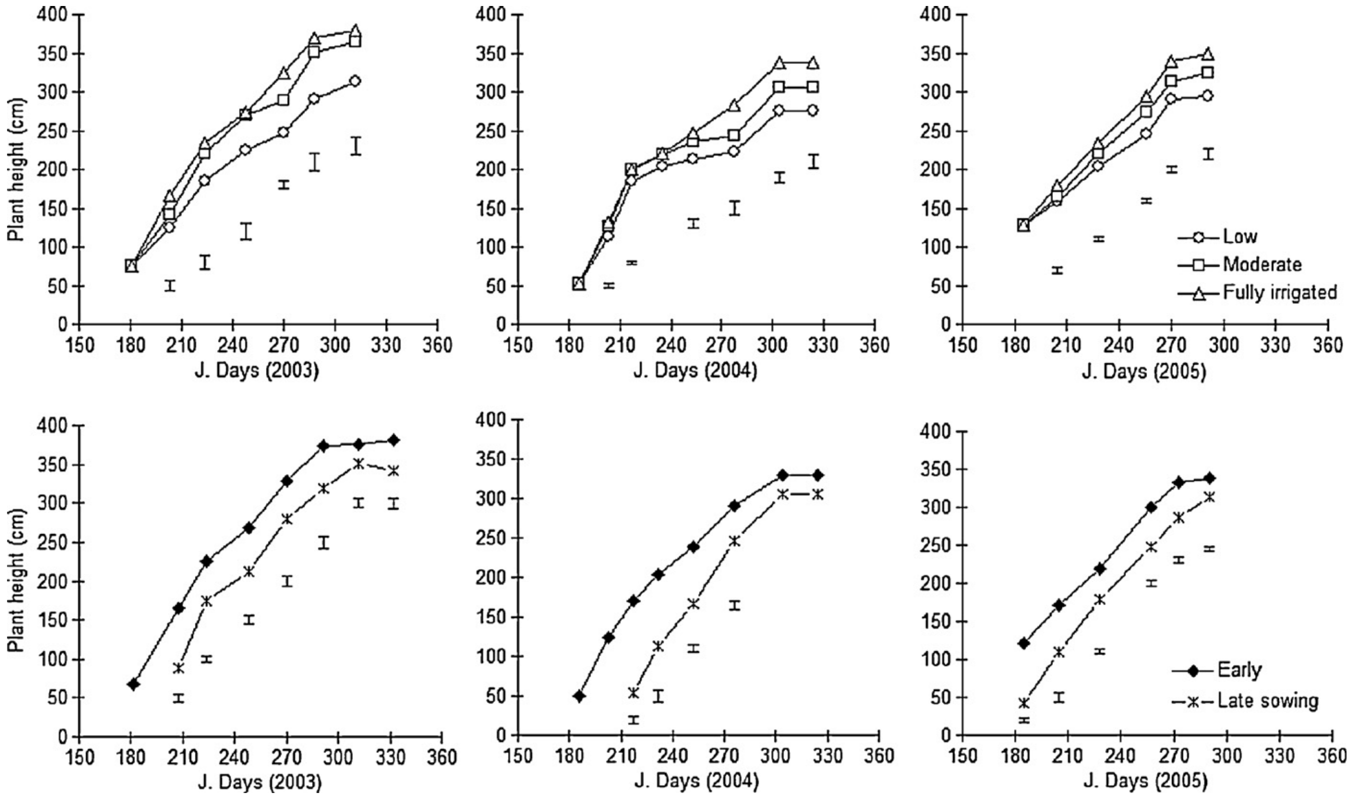

Fig. 2. Plant height evolution of kenaf as affected by three irrigation applications (early crop-above) and two sowing dates (full irrigation-below) in central Greece in 2003–2005. Vertical bars indicate LSD at $P < 0.05$ (if applicable).

(*Gossypium hirsutum* L.) a crop in the same family with kenaf (Malvaceae) is largely cultivated in this region, achieving yields of 3–4 t ha^{-1}.

3.2. Growth indices

3.2.1. Plant height

No significant interactions ($P > 0.05$) among the studied factors in any of the two experiments were observed. Fig. 2 illustrates that plant height evolution of kenaf was significantly affected by irrigation input and sowing date ($P < 0.05$). Contrarily, no significant differences of plant height were observed for the different cultivars, plant densities and N-fertilization rates in all studied years (Table 2), which is in accordance with previous studies (Alexopoulou et al., 2000; Kipriotis et al., 2007; Manzanares et al., 1997; Muchow, 1979; Patanè et al., 2007). Kenaf, after an initial period of crop establishment (about 28 days or 415 °C-days), reached a height of about 60 cm. Then on, plant height increased almost linearly until flowering, when stem elongation ceased due to transition to the reproducing stage. It is noticeable that the rates of plant height increase (early crop: 2.7 cm d^{-1}; late crop: 3.1 cm d^{-1}; Fig. 2) run almost parallel to each other so that the difference in plant height remained almost identical, and the greater final height of the early crop was due to the larger time period available for vegetative growth (see also Fig. 7b). Under the prevailing soil-weather conditions and the particular cultivation techniques, final plant height was 325–380 cm for the early crops to 300–345 cm for the late crops upon flowering (full irrigation). Upon moderate water shortage, plant height remained by 60–75 cm lower (viz. 270–305 cm; Fig. 2). Furthermore, kenaf basal stem diameter during flowering ranged from 1.96 to 2.58 cm, without remarkable differences among the study factors (data not shown).

3.2.2. Leaf area index

Figs. 3 and 4 illustrate the LAI evolution for all tested factors. Particularly, Fig. 4 shows that significant differences ($P < 0.05$) among irrigation treatments and sowing dates were found throughout the growing periods in all studied years. Contrarily, no statistical differences were found for the two different cultivars, plant densities and the four fertilization rates (Fig. 3).

Similarly to plant height, the LAI increased initially at small rates reaching a value close to 1, about 1 month after emergence (415 °C-days). This is a sensitive period for kenaf growth due to weed competition. Thereafter, the LAI increased at considerable high rates, reaching maximum values above 3.5 in all cases (1048 °C-

Table 2
Plant height (cm) of Kenaf upon flowering.

	2003	2004	2005
Exp-1			
Cultivars			
cv. T2	369	319	325
cv. E41	359	315	329
LSD$_{0.05}$[a]	ns[b]	ns	ns
Plant density			
20 pl m^{-2}	373	319	329
30 pl m^{-2}	355	315	325
LSD$_{0.05}$	ns	ns	ns
Exp-2			
N-fertilization			
0	367	316	327
50 kg ha^{-1}	352	301	328
100 kg ha^{-1}	358	314	320
150 kg ha^{-1}	328	292	315
LSD$_{0.05}$	ns	ns	ns

[a] LSD: least significant difference at $P < 0.05$.

[b] ns: no significant.

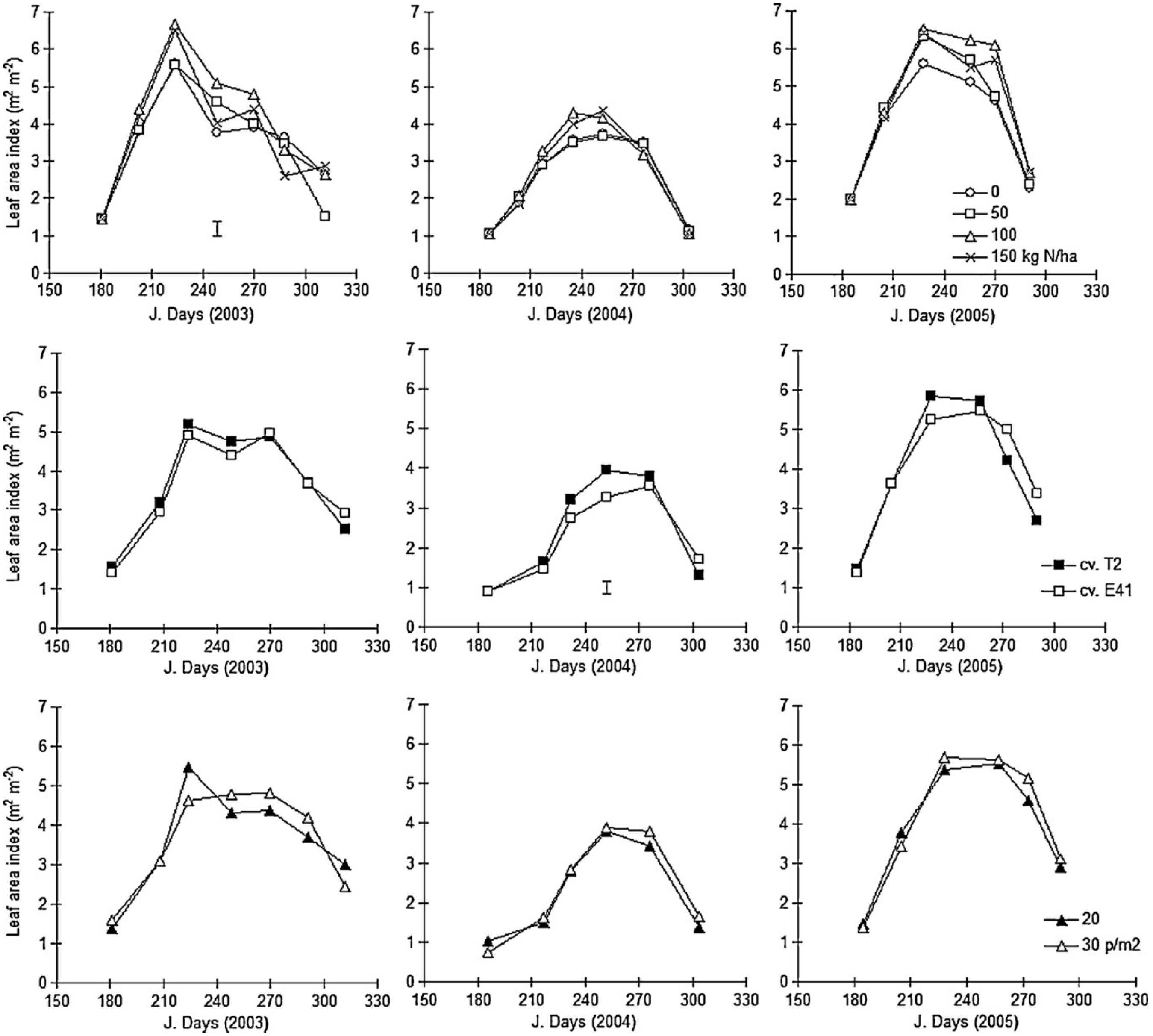

Fig. 3. Leaf area index evolution of kenaf as affected by four N-fertilization rates (upper panel), two cultivars (middle panel) and two plant densities (lower panel) in central Greece for all study years. Vertical bars indicate LSD at $P < 0.05$ (if applicable).

days) and remained at high levels for about 1.5–2.0 months (until mid-September). Then the LAI decreased gradually until 50% of flowering due to leaf ageing and senescence. The LAI dropped to zero values approximately 2–3 weeks after flowering completion, depending on the prevailing weather conditions (temperatures <10 °C).

It is remarkable that the earlier the sowing of the crop, the higher the obtained maximum LAI value (range: 3.9–6.8; Fig. 4) and the larger the period that the canopy is practically closed (light interception >95%; authors unpublished data). Actually, in 2005 that very early sowing was possible (April 6th), LAI_{max} reached 6.4; in 2003 with sowing on May 20th, the LAI_{max} reached 5.5 whereas in 2004, that early sowing was not possible before June 1st, the LAI_{max} did not exceed 4.2 (Fig. 4-below). The late crop in the same year reached LAI values ≥ 3 only for 1 month within the growing period, meaning that sowing of kenaf later than early June may result in inadequate canopy closure and finally a drastic yield reduction (see later). Based on our findings, a linear LAI_{max} reduction after Julian day 130 may be of the type: $LAI_{max} = 6.5–0.07 \times (JD-130)$. Fig. 4-above shows that LAI fluctuated more than 0.5–1 unit lower in the drier plots comparing to the wet plots resulting in somewhat lower growth rates and final productivity (see later). However, the LAI course even under low water inputs (25% of ETm) remained at satisfactory levels.

LAI comprises very important index for assessing biomass accumulation, whereas accurate estimation of the dynamic pattern of LAI is central in crop modelling (Goudriaan and van Laar, 1994). Apart from the documented effect of temperature sum on LAI (Danalatos, 1993), in the case of kenaf there is evidence that the rate of leaf senescence is also modified by the day-length, since the plant passes through development phases by modifying leaf properties. This is also reflected from the course of the specific leaf area (SLA; m^2 green leaf kg^{-1}) for kenaf (data not shown) where the crop during the vegetative stages (emergence to mid-August) achieved maximum values of about 20–22 $m^2\,kg^{-1}$ and thereafter decreased exponential to 10–12 $m^2\,kg^{-1}$ during flowering (October) following the decrease in day-length (from 13.5 to 10.9 h) and temperature as well.

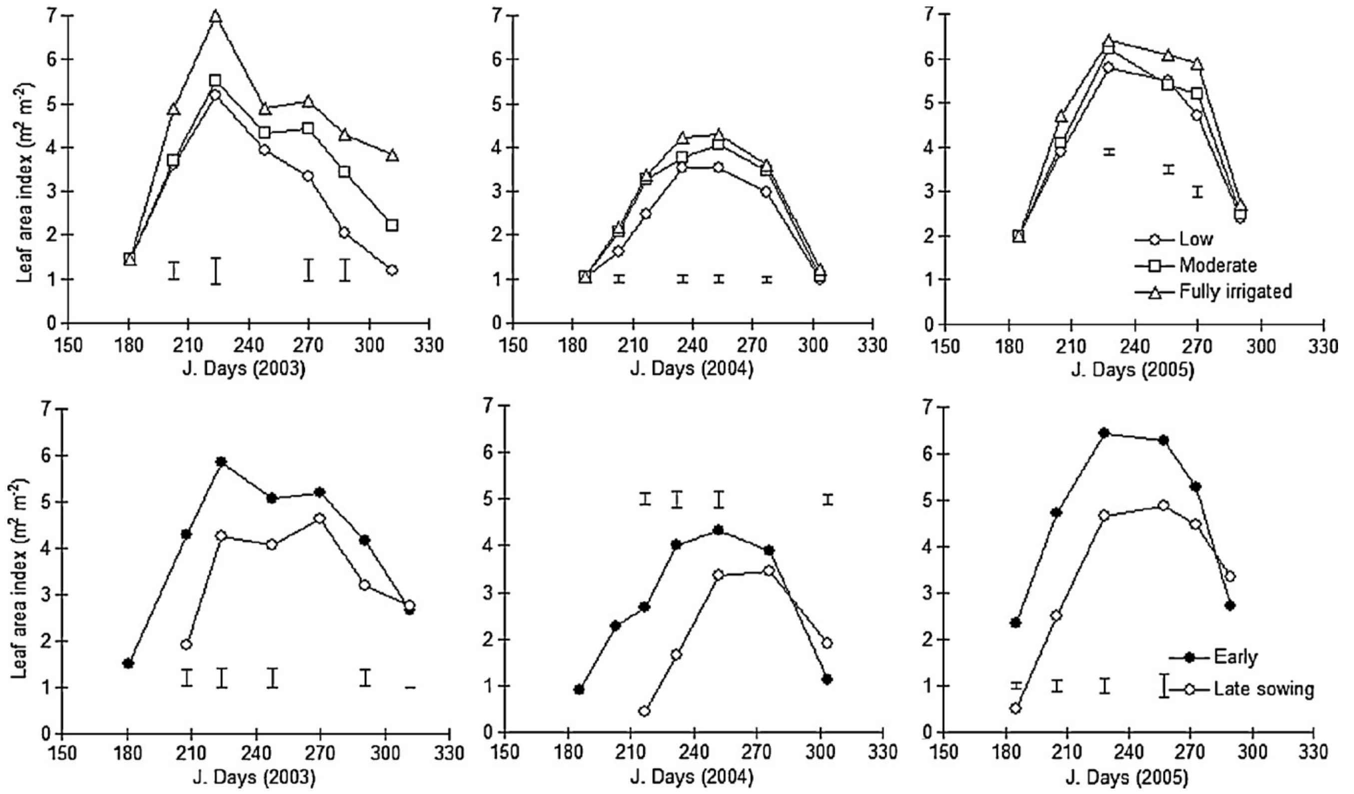

Fig. 4. Leaf area index evolution of kenaf as affected by three irrigation inputs (above) and two sowing dates (below), in central Greece for all study years. Vertical bars indicate LSD at $P < 0.05$ (if applicable).

3.3. Biomass accumulation

No significant interactions ($P > 0.05$) among the studied factors in any of the two experiments were observed. Figs. 5 and 6 illustrate the evolution of total dry biomass for all studied factors. Fig. 5 shows that no statistical differences were found for the two different cultivars, the two plant densities and the four fertilization rates. On the opposite, significant differences ($P < 0.05$) in growth rates and biomass productivity were found among sowing dates and irrigation treatments throughout the growing periods in all study years (Fig. 6).

3.3.1. Cultivar effect

Fig. 5-middle shows that total dry matter of both studied varieties increased with almost identical rates throughout the growing period in all study years. The same holds for the growth of the stems (data not shown). This can be attributed to the similar assimilation and respiration rates of the two late-mature varieties. Actually, measured data confirm similar light-response curves and maximum leaf net assimilation rates of about 50–55 kg CO_2 ha^{-1} h^{-1} for both varieties at light saturation and for leaf temperature 25–33 °C (Archontoulis et al., 2005, 2006). Our findings on yield potential agree with previous literature (Alexopoulou et al., 2000; Belocchi et al., 1998; Liu and Labuschagne, 2009; McMillin et al., 1998). Moreover seed production by cvs. Tainung 2 and Everglades 41 is not relevant in our case (central Greece) due to unfavorable weather condition (low air temperatures and high humidity levels) during the seed filling period (from November and onwards).

3.3.2. Plant density effect

Fig. 5-below illustrates that plant population had a minimal effect on growth and final productivity of both kenaf varieties despite the slight superiority in LAI of the denser populations at advanced development stages (Fig. 3). Apparently, under the prevailing climatic conditions, maximum productivity of kenaf may be obtained even with a population of 20 plants m^{-2}. It should be noticed, however, that lower branching and smaller basal stem diameters were observed in the higher densities along with a greater sensitivity to logging after flowering initiation. In the denser plantation, a reduction in plant number per m^{-2} was evident after mid-season, in line with Webber and Bledsoe (2002) and Muchow (1979) findings, i.e. at higher densities (>37 pl m^{-2}) kenaf compensates for the available environmental resources by reducing the plant number. It seems that kenaf individual plants are able to manipulate their growth in response to density without much influencing growth rates and biomass productivity.

3.3.3. Fertilization effect

Unexpectedly, dry biomass of kenaf was not influenced by N-fertilization ($P > 0.05$) in the range of 0–150 kg N ha^{-1} in any of the study years (Fig. 5-above). This is apparently due to the low nitrogen needs of the crop (woody type crop) and the relatively high fertility status of the study soil in combination with the high soil moisture levels. Nitrogen concentration in the stems (harvested product) was measured at 0.7% (range: 0.6–0.9). Thus 15–18 t ha^{-1} stem dry biomass during the harvesting period (see also Table 3) took up some 105–126 kg N ha^{-1}. Apparently, such N amounts could be mineralized annually in the studied soil which is particularly fertile and moist even at deeper horizons. It should be noticed that such soils (Aquic Xerofluvent, USDA, 1975) are characterized by high organic matter contents (1–1.5%) at deeper soil layers as well as high moisture content at great depths, due to the existence of groundwater table that is being artificially kept deeper than 2 m below surface. However, such minimum responses of kenaf growth to N-fertilization have also been reported by some other authors (Kipriotis et al., 2007; Manzanares et al., 1997; Patanè et al., 2007).

Considering N-balance approaches for kenaf restoration, additional caution should be taken, since kenaf produces some

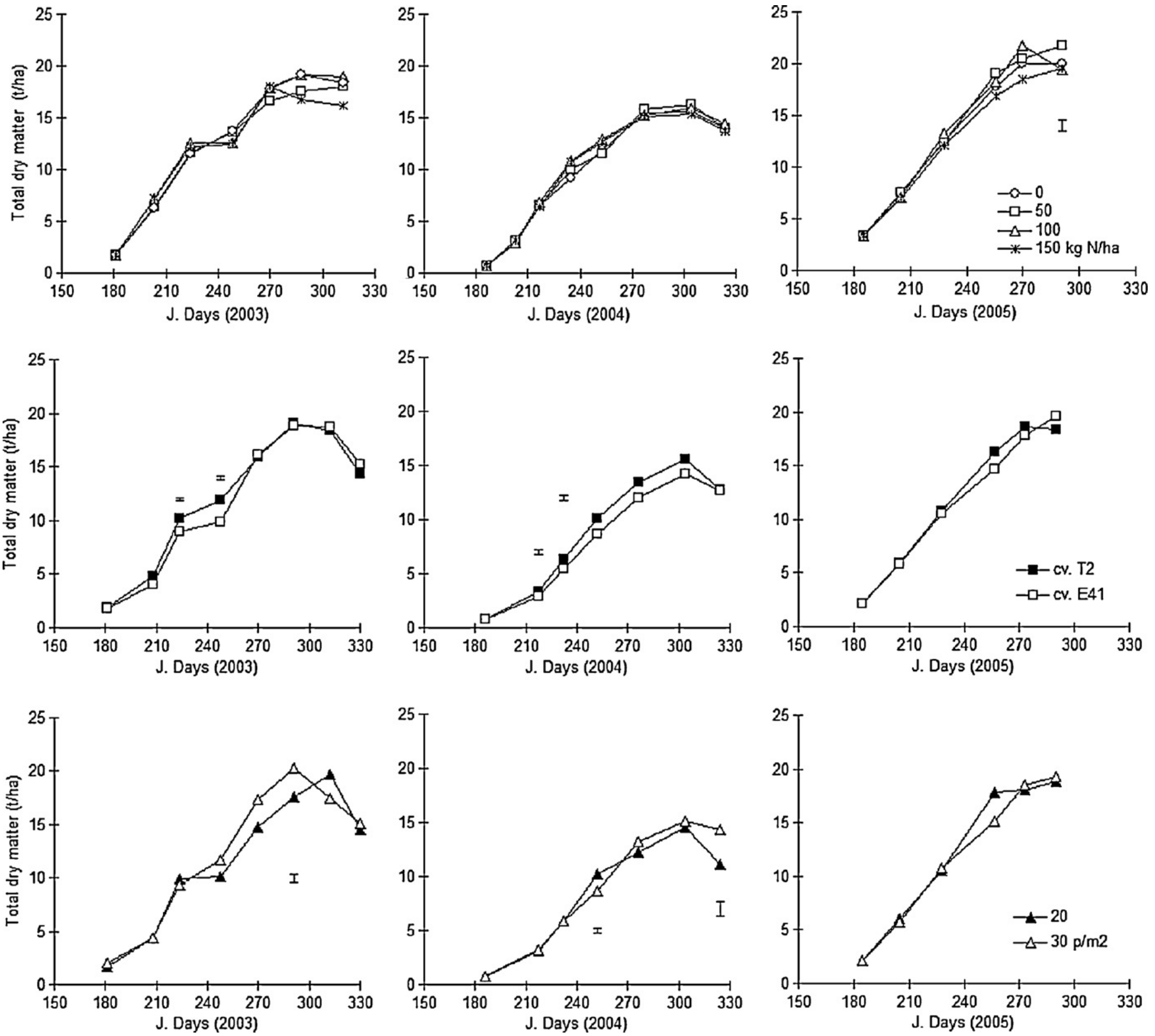

Fig. 5. Total dry biomass as affected by four N-fertilization rates (upper panel), two cultivars (middle panel) and two plant densities (lower panel) in central Greece for all study years. Vertical bars indicate LSD at $P < 0.05$ (if applicable).

3.5–5.0 t ha^{-1} as leaf and petiole biomass (see also LAI; Figs. 3 and 4) that litters and incorporates into the topsoil, providing some 38–55 kg N ha^{-1} as nitrogen fertilization. The nitrogen-use efficiency (NUE) of kenaf was estimated at 142 kg kg^{-1}, which is rather high compared to common agricultural crops (maize: 66–111 kg kg^{-1}, wheat: 83–87 kg kg^{-1}; Jorgensen and Schelde, 2001).

3.3.4. Irrigation effect

Contrary to fertilization, a significant effect ($P < 0.05$) of irrigation on total dry weight was observed in all years and this effect was more pronounced in 2003 (Fig. 6-above). Similar responses were observed also for the stem dry weight (Table 3). It can be seen that until mid-August, growth rates of 187, 217 and 240 kg ha^{-1} day^{-1} could be attained for the I_1-, I_2- and I_3-irrigated plants, respectively. At advanced growth stages, the crop increases only slightly (less than 50 kg ha^{-1} day^{-1} for I_2- and I_3-irrigated plants) in dry matter, while upon flowering the growth was ceased. Maximum (3-year average) total dry weight was observed in all study years upon 50% of flowering (approximated mid-October; Fig. 6-above) which was 15.1, 18.5 and 20.3 t ha^{-1}, for the I_1-, I_2-, and I_3-irrigated plants, respectively. The stem/total dry biomass fraction was rather constant (87%) around flowering, irrespectively of the different irrigation inputs (Table 3 and Figs. 5 and 6). The rest 13% was distributed to leaves and flower buds.

One important result is that the reduction in biomass production due to water shortage was only 9% and 26%, comparing I_2 vs. I_3 and I_1 vs. I_3, respectively (Fig. 6-above). This is due to the positive effect of the high soil moisture content of the subsoil of the particular aquic soil, meaning that under the prevailing soil-weather conditions the growth rates and stem and total biomass productivity of I_3 plants are the potential ones in all study years, considering also the previous discussion. This is very important, as this maximum growth rates and productivity can serve as reference for the assessment of crop performance under production situations at hierarchically lower input and management levels. As far as the study soil is concerned, which represents extensive areas in the Thessaly lowland, it appears that it may supply roots with sub-

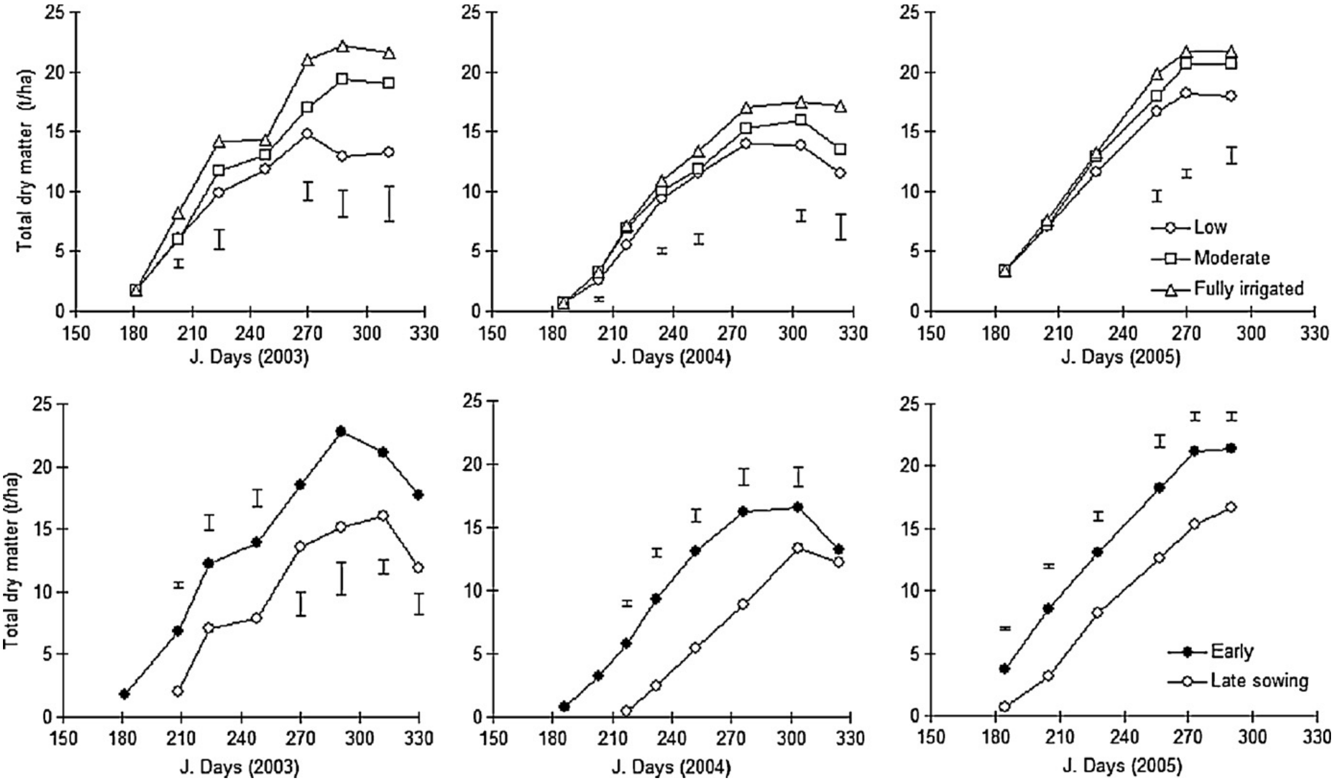

Fig. 6. Total dry biomass as affected by three irrigation inputs (above) and two sowing dates (below), in central Greece for all study years. Vertical bars indicate LSD at $P < 0.05$ (if applicable).

stantial amounts of moisture to sustain considerably high biomass yields (near to potential) with only supplemental irrigation (viz. 250 mm per year). Even in the marginal situation of 2–3 irrigation applications with totally some 90–130 mm of water, a no modest total biomass of 13–17 t ha^{-1} may be attainable.

Table 3
Kenaf stem dry biomass (t ha^{-1}) upon flowering.

	2003	2004	2005
Exp-1			
Sowing time			
Early	17.3	14.8	18.5
Late	11.6	10.8	13.7
LSD$_{0.05}$[a]	5.1	3.8	1.3
Cultivars			
cv. T2	14.0	13.4	15.8
cv. E41	14.9	12.2	16.4
LSD$_{0.05}$	ns[b]	ns	ns
Plant density			
20 pl m^{-2}	13.6	12.4	15.9
30 pl m^{-2}	15.3	13.1	16.3
LSD$_{0.05}$	ns	ns	ns
Exp-2			
Irrigation			
Low	10.4	12.4	14.1
Moderate	15.1	14.4	17.9
Fully	16.6	16.0	18.9
LSD$_{0.05}$	4.1	1.7	2.5
N-fertilization			
0	14.4	14.0	16.4
50 kg ha^{-1}	13.2	14.6	19.1
100 kg ha^{-1}	15.0	14.6	16.0
150 kg ha^{-1}	13.2	13.8	16.5
LSD$_{0.05}$	ns	ns	2.3

[a] LSD: least significant difference at $P < 0.05$.
[b] ns: no significant.

The water-use efficiency (WUE) is commonly examined to provide a more insight into the process efficiency of turning water and CO$_2$ into biomass. Kenaf WUE (defined in this study as the total dry biomass yield divided by the total amount of water applied, including precipitation) ranged from 3.7 to 6.6 g DM kg water^{-1}, with respect to irrigation application (100–25% of ETm, respectively). In a similar study on a sandy loam soil in California, the WUE (same approach) was much lower (viz. 1.5–4.4; Banuelos et al., 2002) compared to our findings. However, Quaranta et al. (2000) provided WUE values for kenaf (same approach) from 2.2–4.1 for dry soils to 3.5–6.3 for moister (aquic) soils, which is in line with our estimates. The higher WUE values obtained in aquic soils are apparently due to the great positive effect of the moisture regime in the soil profile.

3.3.5. Effect of sowing time

Fig. 6-below underlines the paramount effect of sowing time (and emergence) on biomass productivity in all studied years. It appears that this is rather the result of the greater period that is available for vegetative growth of the early vs. the late plantings, and not due to great differences of the growth rates for each particular year (Fig. 7b). Actually, from 30 to 40 days after emergence (415 °C-days), the crop reaches a total biomass of about 1.1 t ha^{-1} and until the end of September kenaf grows almost linearly, performing similar high growth rates of 170–200 kg ha^{-1} day^{-1} for the early plantings to 150–180 kg ha^{-1} day^{-1} for the late plantings. As a result, the growth lines for both early and late plantings run almost parallel to each other, so that the difference in the final biomass productivity could be attributed mainly to the period available for growth, making crucial the earliness of sowing and emergence on crop production (Fig. 7). This is the main reason of the considerably lower (>38%) biomass yields measured in the late sowings (Fig. 7a). This is in accordance with previous studies in Mediterranean region (Manzanares et al., 1997; Sortino et al., 2005).

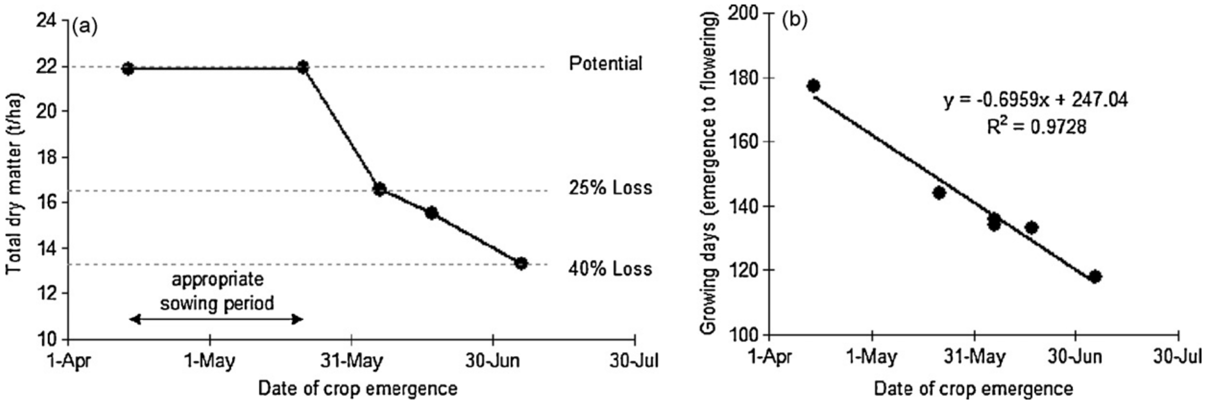

Fig. 7. Total dry biomass yield (a) and growing period in days (b) vs. the date of kenaf emergence, in central Greece in 2003–2005.

Under the prevailing conditions of central Greece, proper sowing time for kenaf might be from mid-April until the second decade of May, when air temperatures exceed 15 °C, prompting at a fast emergence (Fig. 7a). With an early sowing, the vegetative phase is expanded (more time for growth, Fig. 7b) before the crop enters to critical photoperiodic levels. Under central Greek conditions (38–40°N), this critical level was found to be at the end of September, where there is a substantial decrease in photoperiod (around 12.0 h) and the crop enters the flowering phase signaling the end of growing period (approximately mid-October). Such findings are in accordance with Gray et al. (2006) reporting that for kenaf cultivars growing between 30° and 40° northern latitudes, anthesis occurs when day-length has decreased to about 12.5 h. The observed decrease in biomass yields (Figs. 5 and 6) during October is mainly due to leaf fall (see also LAI; Fig. 4).

In most cases, maximum growth rates were observed during early vegetative phase (July–mid-August) reaching 220–240 kg ha^{-1} day^{-1}. The observed maximum growth rates agree with the values reported from Australia (Charles-Edwards et al., 1983). Moreover in our case, the growth rates are fairly well explained by the favorable climatic conditions for leaf photosynthesis and plant growth that occurred in the study area and the adequate moisture and nutrient supply from the study soil. Indeed during the growing period, the mean day-time air temperature was 29 °C (range: 25.9–30.1 °C) which is near-optimum temperature for kenaf growth (viz. 31 °C, Carberry et al., 1992) and leaf photosynthesis (viz. 25–33 °C, Archontoulis et al., 2005). In the same time, global radiation exceeds 600 W m^{-2}, for the biggest part of the day-time implying maximum leaf assimilation rates (50 kg CO$_2$ ha^{-1} d^{-1}; Archontoulis et al., 2005) and considering also the closed green canopy, maximum canopy assimilation rate were achieved.

In the years 2003 and 2005, the maximum biomass production was equal and around 22 t ha^{-1}, and based on the above (Sections 3.3.3–3.3.4) this might be the average maximum kenaf productivity for the study area. The lower productivity attained in 2004 was due to the remarkable delay in sowing (Figs. 6-below and 7a). Based on our results, the maximum dry matter production (TDM in t ha^{-1}) in the study area (central Greece) can be approximated from the available growing period in days (D) with the empirical formula:

$$\mathrm{TDM} = 22.0 \text{ for } \mathrm{D} > 155 \text{ days.}$$

$$\mathrm{TDM} = 0.2547 \times \mathrm{D} - 17.365 \ (n = 6,\ R^2 = 0.97) \text{ for } \mathrm{D} \leq 155 \text{ days.}$$

Regarding the economic product of kenaf (viz. stems), stem weight increased in a similar way with total biomass, significantly affected by the sowing time. During flowering (October) stems comprised 77–87% of the total dry biomass (Table 3). The obtained biomass productivities of kenaf here are among the highest reported worldwide (Amaducci et al., 2000; Baldwin and Graham, 2006; Banuelos et al., 2002; Belocchi et al., 1998; Bhardwaj et al., 2005; Carberry et al., 1992; McMillin et al., 1998; Manzanares et al., 1993; Manzanares et al., 1997) and it is in line with other reports on the study cultivars grown in similar geographical range (38–41°N), under similar climatic conditions and management practices (Alexopoulou et al., 2000; Banuelos et al., 2002; Belocchi et al., 1998; McMillin et al., 1998; Meints and Smith, 2003; Webber and Bledsoe, 2002).

4. Conclusions

Kenaf varieties Tainung 2 and Everglades 41 adapt very well under the environmental conditions of (central) Greece, achieving high potential biomass (22 t ha^{-1}) and stem yields (18 t ha^{-1}). Particularly high growth rates (180–220 kg ha^{-1} day^{-1}) can be obtained throughout the growing season, but the period available for growth plays very important role in maximizing crop productivity. Sowing should take place from mid-April to mid-May, when air temperature stabilizes above 15 °C, in otherwise a drop in productivity is inevitable that may reach 40% or more. Aquic Xerofluvents are very fertile alluvial soils occupying large parts of Thessaly, the country's major lowland. In such soils, high growth rates and biomass productivity may be attainable for plant densities 20–30 plants m^{-2} under supplemental irrigation (50% ETm) and under no to modest fertilizer application. The introduction of the above kenaf varieties in crop rotation schemes in Greece should be seriously considered for paper pulp and bio-energy production in the near future.

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References

Alexopoulou, E., Christou, M., Nicholaou, A., Mardikis, M., 2004. BIOKENAF: a network for industrial products and biomass for energy from kenaf. In: Van Swaalj, W.P.M. (Ed.), Biomass for Energy, Industry and Climate Protection. Proceedings of the 2nd World Biomass Conference. 10–14 May, Roma, Italy, pp. 2040–2043.

Alexopoulou, E., Christou, M., Mardikis, M., Chatziathanasiou, A., 2000. Growth and yields of kenaf varieties in central Greece. Ind. Crops Prod. 11, 163–172.

Amaducci, S., Amaducci, M.T., Benati, R., Venturi, G., 2000. Crop yield and quality parameters of four annual fibre crops (hemp, kenaf, maize, sorghum) in the North of Italy. Ind. Crops Prod. 11, 179–186.

Archontoulis, S.V., Struik, P.C., Danalatos, N.G., 2005. Leaf photosynthesis of kenaf (cv. Everglades 41) as affected by different light intensity and temperature regimes. In: Proceedings of the 14th European Biomass Conference, 17–21 October, Paris, France, pp. 414–417.

Archontoulis, S.V., Struik, P.C., Danalatos, N.G., 2006. Diurnal leaf gas exchange patterns of two kenaf genotypes at two leaf positions. In: International Conference, on Information Systems, Sustainable Agriculture, Agro-environment and Food technology, September 20–23, Volos, Greece, pp. 423–431.

Banuelos, G.S., Bryla, D.R., Cook, C.G., 2002. Vegetative production of kenaf and canola under irrigation in central California. Ind. Crops Prod. 15, 237–245.

Baldwin, B.S., Graham, J.W., 2006. Population density and row spacing effects on dry matter yield and bark content of kenaf (*Hibiscus cannabinus* L.). Ind. Crops Prod. 23, 244–248.

Bhangoo, M.S., Tehrani, H.S., Henderson, J., 1986. Effects of planting date, nitrogen levels, row spacing and plant population on kenaf performance in San Joaqium Valley. Agron. J. 78 (4), 600–604.

Belocchi, A., Quaranta, F., Desiderio, E., 1998. Yields and adaptability of kenaf varieties (*Hibiscus cannabinus*) for paper pulp in central Italy. In: Sustainable Agriculture for Food, Energy and Industry. James & James (Science publishers) Ltd, pp. 1039–1049.

Bhardwaj, H.L., Webber III, C.L., Sakamoto, G.S., 2005. Cultivation of kenaf and sunn hemp in the mid-Atlantic United States. Ind. Crops Prod. 22, 151–155.

Carberry, P.S., Abrecht, D.G., 1990. Germination and elongation of the hypocotyls and radicle of kenaf (*Hibiscus cannabinus*) in response to temperature. Field Crop Res. 24, 227–240.

Carberry, P.S., Muchow, R.C., Williams, R., Sturtz, J.D., McCown, R.L., 1992. A simulation model for kenaf assisting fibre industry planning in northern Australia. I. General introduction and phenological model. Aust. J. Agric. Res. 43, 1501–1513.

Carberry, P.S., Muchow, R.C., 1992. A simulation model for kenaf assisting fibre industry planning in northern Australia. II. Leaf area Development. Aust. J. Agric. Res. 43, 1515–1526.

Charles-Edwards, D.A., Muchow, R.C., Wood, I.M., 1983. Effect of sowing date on the growth and yield of kenaf (*Hibiscus cannabinus*) grown under irrigation in tropica Australia. III. Physiological analysis of growth. Field Crops Res. 7, 103–113.

Danalatos, 1993. Quantified analysis of selected land use systems in the Larissa region, Greece. Wageningen Agricultural University, PhD Thesis, ISBN 90-5485-063-9, Wageningen, The Netherlands, 370 pp.

Doorembos, J., Pruitt, W.O., 1977. Crop water requirements. In: Irrigation and Drainage Paper No. 24. FAO, United Nations, Rome.

Francois, L.E., Donovan, T.J., Mass, E.V., 1992. Yield, vegetative growth and fiber length of kenaf grown on saline soil. Agron. J. 88, 592–598.

Gray, L.N., Collavino, N.G., Simon, G.E., Mariotti, J.A., 2006. Diallelic analysis of genetic effects determining days to flowering in kenaf. Ind. Crops Prod. 23, 194–200.

Goudriaan, J., van Laar, H.H., 1994. Modelling Potential Crop Growth Processes. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Jorgensen, U., Schelde, K., 2001. Energy crop water and nutrient use efficiency. Report for the International Energy Agency, IEA Bioenergy Task 17, Short Rotation Crops, Denmark, 38 pp.

Kipriotis, E., Alexopoulou, E., Papatheohari, Y., Moskov, G., Georgiadis, S., 2007. Cultivation of kenaf in north-east Greece. Part II. Effect of variety and nitrogen on growth and dry yield. J. Food Agric. Environ. 5 (1), 135–139.

Kuchindra, N.C., Ndahi, W.B., Lagoke, S.T.O., Ahmed, M.K., 2001. The effects of nitrogen and period of weed interference on the fibre yield of kenaf (*Hibiscus cannabinus*) in the northern Guinea Savanna of Nigeria. Crop Prot. 20, 229–235.

Liu, Y., Labuschagne, M.T., 2009. The influence of environment and season on stalk yield in kenaf. Ind. Crops Prod. 29, 377–380.

Manzanares, M., Tenorio, J.L., Manzanares, P., Ayerbe, L., 1993. Yield and development of kenaf (*Hibiscus canabinus* L.) crop in relation to water supply and intercepted radiation. Biomass Bioenergy 5 (5), 337–345.

Manzanares, M., Tenorio, J.L., Ayerbe, L., 1997. Sowing time, cultivar, plant population, and application of N fertilizer on kenaf Spain's central plateau. Biomass Bioenergy 14 (4), 263–271.

McMillin, J.D., Wanger, M.R., Webber III, C.L., Mann, S.S., Nichols, J.D., Jech, L., 1998. Potential for kenaf cultivation in south-central Arizona. Ind. Crops Prod. 9, 73–77.

Meints, P.D., Smith, C.A., 2003. Kenaf seed storage duration on germination, emergence and yield. Ind. Crops Prod. 17, 9–14.

Muchow, R.C., 1979. Effects of plant population and season on kenaf (*Hibiscus cannabinus* L.) grown under irrigation in tropical Australia. II. Influence on growth parameters and yield prediction. Field Crops Res. 2, 67–76.

Muchow, R.C., 1992. Effect of water and nitrogen supply on radiation interception and biomass accumulation of kenaf (*Hibiscus canabinus*) in a semi-arid tropical environment. Field Crop Res. 28, 281–293.

Muchow, R.C., Carberry, P.S., 1993. A simulation model for kenaf assisting fibre industry planning in northern Australia. V. Impact of different crop trait. Aust. J. Agric. Res. 44, 731–744.

Nielsen, D.C., 2004. Kenaf forage yield and quality under varying water availability. Am. J. Agron. 96, 204–213.

Patanè, C., D'Agosta, G.M., Mantineo, M., Cosentino, S.L., 2007. Radiation interception and use by kenaf (*Hibiscus cannabinus* L.) canopy under different water and nitrogen supply. In: Proceeding of 15th European Biomass Conference, Berlin, Germany, pp. 791–794.

Quaranta, E., Belocchi, A., Bottazzi, P., Monotti, M., Del Pino, A.M., Desiderio, E., 2000. Limited water supply on kenaf (*Hibiscus cannabinus* L.) in central Italy. Ital. J. Agron. 4 (1), 1–9.

Steel, R.G.D., Torrie, J.H., 1982. Principles and Procedures of Statistics. A Biometrical Approach, 2nd ed. McGraw-Hill, Inc, p. 633.

Sortino, O., Patanè, C., D'Agosta, G., Cosentino, S.L., 2005. Effect of sowing time on seed production of kenaf (*Hibiscus cannabinus*) in Sicily. In: Proc. of the 14th Biomass Conference, Paris, France, pp. 145–148.

USDA (Soil Survey Staff), 1975. Soil taxonomy. Basic system of soil classification for making and interpreting soil surveys. Agricultural Handbook, vol. 466. USDA, Washington, DC, p. 754.

Webber III, C.L., 1993. Crude protein and yield components of six kenaf cultivars as affected by crop maturity. Ind. Crops Prod. 2, 27–31.

Webber III, C.L., 1996. Response of kenaf to nitrogen fertilization. In: Janick, J., Simon (Eds.), Progress in New Crops. Wiley, New York, pp. 404–408.

Webber III, C.L., Bledsoe, V.K., 2002. Kenaf yield components and plant composition. In: Janick, J., Whipkey, A. (Eds.), Tends in New Crops and New Uses. ASHS Press, Alexandia, VA, pp. 348–357.

Wood, I.M., Muchow, R.C., 1980. Estimation of optimal rate of application of nitrogen for kenaf (*Hibiscus cannabinus*) harvested at different ages for paper pulp production. CSIRO Aust. Trop. Agron. Tech. Mem. 25.

Wood, I.M., Muchow, R.C., Ratcliff, 1983. Effect of sowing date on the growth and yield of kenaf (*Hibiscus cannabinus*) grown under irrigation to tropical Australia. II. Stem production. Field Crop Res. 7, 91–102.