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Fungal diseases and inappropriate sowing dates, the most important reducing factors in cumin fields of Iran, a case study in Khorasan provinces

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ABSTRACT

A simple model was constructed, tested and used to determine the potential yield of cumin (*Cuminum cyminum*). Using model outputs and data obtained from 228 fields, yield gap was determined. Yield gap varied considerably among regions (from 2.42 to 0.68 ton ha^{-1}). Stepwise regression on data collected from fields showed that 73% of yield gap variation in 228 fields could be explained by fungal diseases (*Fusarium oxysporum* and *Alternaria burnsii*), inappropriate sowing dates and successive planting. Therefore, these were considered to be the main reducing factors in the studied regions, with 38% contributed by fungal diseases, 30% by sowing date and 5% by successive planting. When 67% of surveyed fields (averaged for all fields) were infected with these diseases and when there was a 3-mm increment in precipitation, infection increased about 1%. Our results indicated that 1% of the fungal infection increase equals to a yield loss of 150 kg per hectare. Sowing date of 63% of fields were also not within the appropriate range. Therefore, appropriate sowing date and all possible approaches to alleviate the effects of fungal diseases are the most fundamental advices to fill the gap between potential and actual yield of cumin in Khorasan provinces, Iran. Detailed descriptions of the model, important physiological parameters and other important state variables are also presented.

1. Introduction

Determination of potential yield, finding yield gap and optimization of these systems to decrease yield gap can be considered as three hierarchical steps to increase production and farmers' income. To optimize production systems, it is essential to determine yield gap and to gather yield gap knowledge on the theoretical ceiling of production under different climatic conditions.

Crop simulation models have been used to determine potential yield in different crops, such as wheat (Aggarwal and Kalra, 1994; Pathak et al., 2003; Wu et al., 2006), peanut (Meinke and Hammer, 1995), rice (Pathak et al., 2003) and maize (Binder et al., 2008). These kinds of models have also been used to evaluate yield gaps in different crops such as wheat (Calvino and Sadras, 2002; Kalra et al., 2007), rice (Haefele et al., 2001; Yang et al., 2008), sorghum and pearl millet (Murty et al., 2007), groundnut (Boote et al., 1991) and soybean (Calvino et al., 2003). Such process-based simulation models have not been developed and applied for many crops such as cumin (*Cuminum cyminum* L.). Cumin is an annual Umbelliferous plant commonly cultivated in arid and semi-arid regions of Iran, especially in Khorasan provinces. The crop is generally grown in sandy loam to clay soils during the winter season using irrigation (Lodha, 1995). Despite the relative importance of this medicinal plant in crop rotations of arid and semi-arid regions and many advantages such as low water requirements and its high value in agricultural exports, it has not been adequately studied and there is not much information on potential yield of the current cultivated area.

This study was aimed to develop a simple model to calculate cumin potential yield and yield gap. Because cumin is a special crop in many regions of Iran, there is paucity of information from this crop to allow its simulation by detailed process-based models. Therefore, our simple model is to simulate potential dry matter and seed yield of cumin. Then, we used the model results to find yield

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Abbreviations: SFP, seed filling period; RUE, radiation use efficiency; F_{abs}, fraction of absorbed radiation; LEC, light extinction coefficient; I, intercepted radiation; DEVS, development stage; LW, leaf weight; SGA, specific green area; PP, photoperiod; CPP, critical photoperiod; DEVR, development rate; DTT, daily thermal time; GLA, green leaf area; TDM, total dry matter; GAI, green area index; HI, harvest index.

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gaps in different cultivated lands. Finally, we provide an overview on the probable causes of the observed gap.

2. Materials and methods

2.1. General overview

The model (CUMMOD) simulates daily dry matter as a product of intercepted radiation (as a function of incident radiation, green area index (GAI) and light extinction coefficient (LEC) by radiation use efficiency (RUE)). The model operates on a daily time step using average air temperature and intercepted radiation. Dry matter (DM) production is partitioned with crop development stages (DEVS; in phenology sub-component), which are divided into two phases (before and after flowering), whose duration is calculated from a thermal sum (°C days) modified by day length, as needed.

The parameters to build the model [such as LEC, RUE, maximum harvest index (HI), critical photoperiod, partitioning coefficients (PC) to different organs, specific leaf area and cardinal temperatures, etc.] were calculated by field and laboratory experiments as follows.

To determine the day length response curve, a non-linear model was fitted with the data of a previous study by Nabavi (2003) to the relative development rate of flowering against different day lengths using an iterative optimization method by the NLIN DUD procedure in the SAS program (SAS Institute, 1990).

Cardinal germination temperatures were determined by fitting an intersected lines model to germination rate at seven constant temperatures (varying from 5 to 35 °C, with 5 °C intervals). This independent experiment was carried out at the Faculty of Agriculture, Ferdowsi University of Mashhad, Iran in 2001. Seed yield was quantified as a product of daily DM and daily HI increment after the beginning of the seed-filling period (SFP), which integrated daily from SFP to physiological ripening.

The CUMMOD model uses readily available weather data and does not account for the effects of yield-limiting (water and nutrients) and yield-reducing (weeds, pests and diseases) factors. The model was constructed using data from a 2001 experiment (sown on 22 February and 4 March 2001) and experiments of others (Sadeghi, 1990; Tavousi, 2000; Nabavi, 2003; Kamkar, 2005). All of the experiments were done in well irrigated and fertilized condition and weed and diseases were controlled as needed. The model was tested with data obtained from an independent field experiment (Kafi, 1989) and from 228 fields monitored during the 2001 growing season (for phenological stages and actual yield). Dates of sowing, flowering and physiological maturity were recorded to test the accuracy of the phenology sub-model. In the field experiments, cumin seeds of Mashhad, as a local cultivar, were planted at the research farm of the Faculty of Agriculture, Ferdowsi University of Mashhad, Iran (36° 16′ N, 59° 16′ E; 992.2 m ASL) on 22 February and 4 March 2001 (target density was 120 seedlings per m^2). These regions were selected as they are the main cumin production areas in Khorasan provinces (Razavi, Northern and Southern Khorasan).

Incident and transmitted radiation of the canopy was measured using the Sunscan Canopy Analysis System (Delta-T Devices, U.K.) at different intervals. GAI was measured simultaneously. Solar radiation (I) was determined using the Angstrom equation (Angstrom, 1924) as Eq. (1) (Persaud et al., 1997):

$$I = I_0(a + bn/N)\left(\text{MJ m}^{-2}\ \text{day}^{-1}\right) \tag{1}$$

where I_0, N and n are extraterrestrial radiation, day length, and maximum sunshine duration, respectively. I_0 was calculated based on Goudriaan and Van Laar (1994). Cumulative intercepted radiation was calculated as daily radiation multiplied by the fraction of absorbed radiation ($F_{\text{abs}} = 1 - \exp^{-\text{LEC.GAI}}$) and all the values obtained daily throughout the growing season were summed.

Allocation of DM to leaf + stem and reproductive organs was calculated for each sampling interval as Rizzalli et al. (2002). Specific green area was calculated by numerous simultaneous measurements during growing season on green area and correspondent weight, then green area (y) and correspondent weight (x) were plotted. Relative constant slope of fitted line to this plot was considered as cumin SGA. Green area measurements were also made periodically during the growing season by destructively sampling a 1-m row, and measuring the green area with a leaf area meter (Delta-T Device, UK). Green area in the model was also calculated by multiplying the value of daily DM allocated to the leaf + stem by SGA (specific green area), which was equal to 110 $\text{cm}^2\ \text{g}^{-1}$.

RUE was estimated as the slope of the linear regression ($y = a + bx$) of cumulative shoot DM versus cumulative intercepted radiation. The LEC was determined from the slope of the regression line between the natural logarithm of radiation transmission and leaf area index (LAI) (Monteith, 1965). HI was calculated as the ratio of seed yield to the total accumulated dry matter (ADM). Absorbed radiation is modeled from the law of Lambert–Beer (Monsi and Saeki, 1953).

Non-linear functions were fitted using the iterative optimization method by Solver as an add-ins tool of Microsoft Excel (2003). The algorithm of model has presented in Fig. 1.

2.2. Database generation

During the 2001 growing season, phenological events were recorded in 228 fields located in nine common cultivated areas of Khorasan provinces as the main provinces of cumin cultivation in Iran (Table 1). These provinces extend from the North East to the South East of Iran. In addition, general information on the 228 fields was recorded to determine the causes of yield gap. The dataset by Kafi (1989) was used to evaluate model accuracy with respect to DM accumulation, GAI and seed yield.

A photoperiod × air temperature interaction model was used to simulate the length of phase 1. For this purpose, a non-linear (segmented) function (Kamkar et al., 2008; Soltani et al., 2006) was used to describe the temperature function [$f(T)$] in cumin:

$$f(T) = (T - Tb)/(To - Tb) \quad \text{if} \quad T < To \tag{2}$$

$$f(T) = [1 - ((T - To)/(Tc - To))] \quad \text{if} \quad To \le T < Tc \tag{3}$$

$$f(T) = 0 \quad \text{if} \quad T \le Tb \ \text{or} \ T \ge Tc \tag{4}$$

where, T, Tb, To and Tc are mean air temperature, the base, optimum, and ceiling temperature, respectively.

Photoperiod function [$f(p)$] was also evaluated by a non-linear intersected line function as described below:

$$f(p) = a + bx \quad \text{if} \quad x < x_0 \tag{5}$$

$$f(p) = a + bx_0 \quad \text{if} \quad x \ge x_0 \tag{6}$$

where a, b, x and x_0 are intercept, photoperiod sensitivity coefficient, photoperiod and critical photoperiod (CPP), respectively.

In this model, thermal time (TT) of emergence to flowering and flowering to maturity were considered as 420 and 520 degree days, with base and optimum temperatures of 3.5 and 15 °C, respectively. Ceiling temperature was also considered as 30 °C. Each phenological stage occurred when $\sum \text{DTT} = \text{TT}$. Daily thermal time (DTT) was also calculated as Eq. (7):

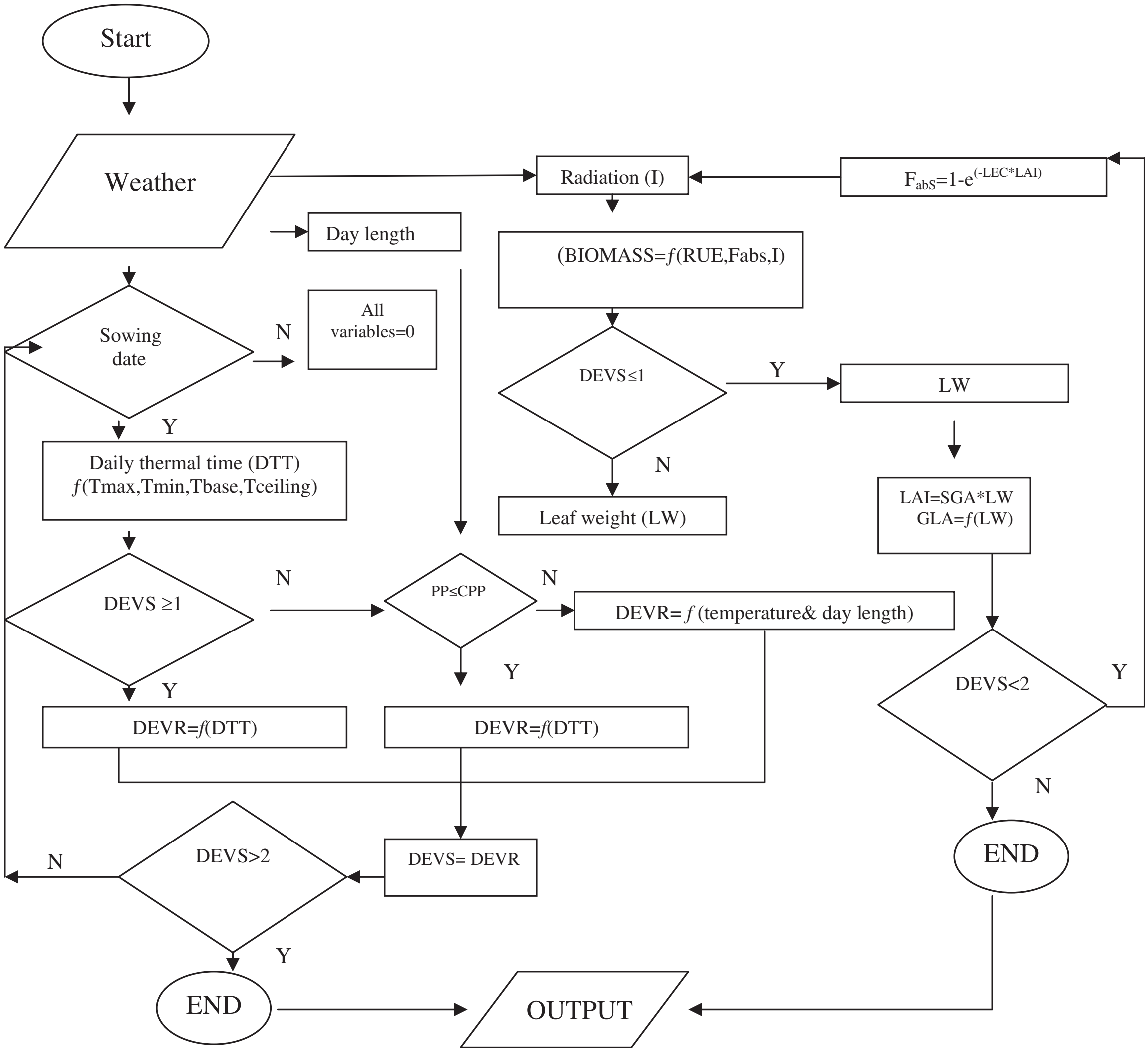

Fig. 1. The algorithm of the CUMMOD. RUE = radiation use efficiency; F_{abs} = fraction of absorbed radiation; LEC = light extinction coefficient; I = intercepted radiation; DEVS = development stage; LW = leaf weight; SGA = specific green area; PP = photoperiod; CPP = critical photoperiod; DEVR = development rate; DTT = daily thermal time; GLA = green leaf area.

$$DTT = (To - Tb) \times f(t) \times f(p) \quad (7)$$

The accuracy of prediction was quantified using the coefficient of determination (R^2) and the root mean square deviation (RMSD) between the number of predicted and observed paired results.

Table 1
Geographical information of nine regions used to test phenological sub-model of the CUMMOD and recording actual yield.

Region	Latitude	Longitude	Altitude (m)	Angstrom coefficient[a]	
				a	b
Sabzewar	36° 12′	57° 43′	977.6	0.276	0.49
Ferdous	34° 01′	58° 10′	1293	0.283	0.45
Kashmar	35° 12′	58° 28′	1109	0.281	0.487
Gonabad	34° 21′	58° 41′	1056	0.259	0.445
Birjand	32° 52′	59° 12′	1491	0.33	0.42
Qaen	33° 43′	59° 10′	1432	0.283	0.458
Mashhad	36° 16′	59° 16′	992.2	0.3	0.37
Neishabour	36° 13′	58° 13′	1213	0.275	0.491
Bojnourd	37° 28′	57° 28′	1091	0.28	0.44

[a] a and b are Angstrom coefficients used in Eq. (1) to determine cloud effects on incident radiation.

3. Results and discussion

The results of the intersected lines model (Fig. 2) show that the response of cumin to photoperiod is a quantitative (facultative) response ($b = 0.95$ and $R^2 = 0.94$) with sensitivity of 0.05 per hour and critical photoperiod (CPP) of 14.17 h.

3.1. Radiation use efficiency and light extinction coefficient

RUE as the slope of accumulated above-ground ADM against accumulated absorbed radiation ($I_0 \times F_{abs}$) was equal to 0.91 g MJ^{-1}. High RUE of cumin may be partially explained by a low fraction of absorbed radiation, because of its low LEC; ≈0.3 (Fig. 3 a-b).

DM partitioning to leaf + stem and reproductive organs showed that after flowering, around 88.2% of DM partitioned to reproductive organs and the rest belonged to the leaf + stem, while all pre-flowering dry matter partitioned to Leaf + stem. In this crop, the stem is a weak but active photosynthetic organ (Kafi, 2002).

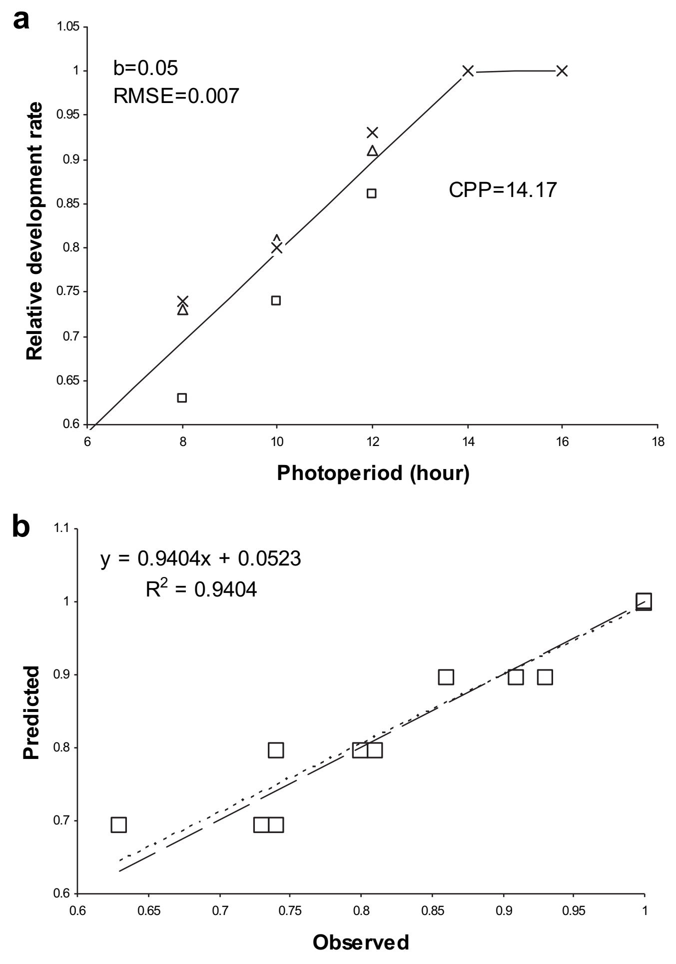

Fig. 2. (a) Non-linear model fitted to relative development rate against photoperiod in three cumin varieties (Azarshar □, Mashhad △ and Biarjamand ×); (b) regressed line between observed against predicted relative development rate. CPP = critical photoperiod (raw data from Nabavi (2003)).

Therefore, in this model, leaves and stem weight have not been separated and GAI was used instead of LAI.

3.2. Green area index

The model was tested with the independent data of Kafi (1989). The simulated and observed green area is presented in Fig. 4a–b. The model predicted total GAI with RMSD = 0.68. Model predictions for the dataset tended to over-predict GAI until flowering and under-predict it from flowering onward. However, it could simulate final GAI properly.

The fraction of absorbed radiation, which was calculated by the model for a test experiment (Kafi, 1989), showed that maximum $F_{abs} = 0.26$ (Fig. 5), which can be interpreted as low DM production in cumin, despite its high RUE.

3.3. Phenology

Model results for sowing date of 28 February 1989 (date used in Kafi, 1989) showed that flowering occurred at 57 DAS, while this was 60 DAS based on the independent data of Kafi (1989). In addition, the model could simulate maturity time accurately. Based on data collected from 228 surveyed fields, flowering and maturity dates simulated with RMSDs of 3.2 and 5.3 days, respectively (data not shown).

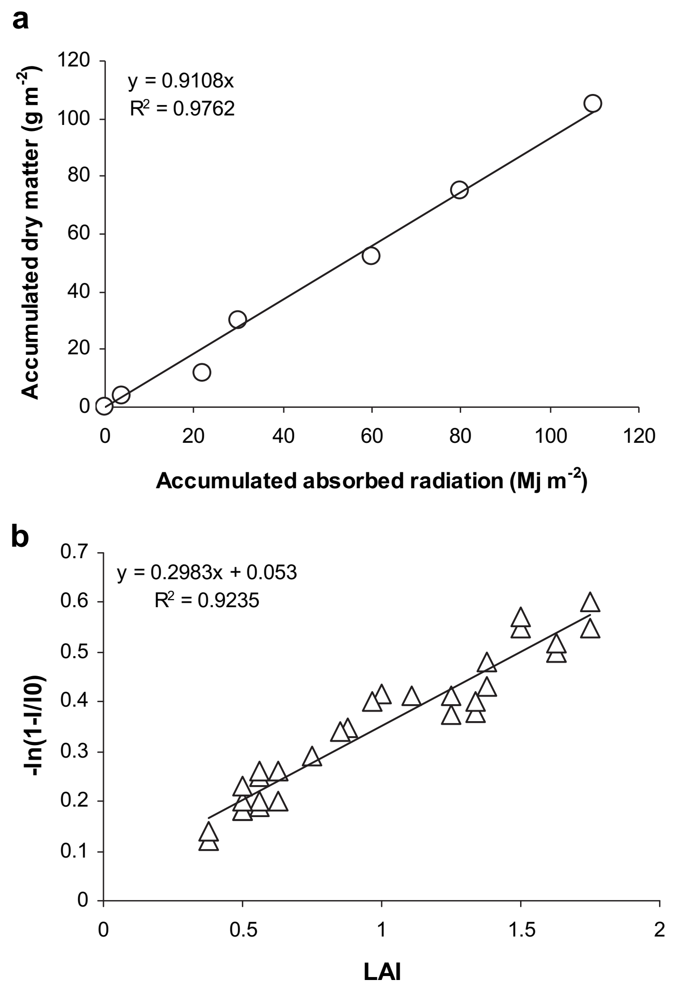

Fig. 3. (a) Dry matter as a function of accumulated intercepted radiation. The slope is the radiation use efficiency (RUE); (b) Illustration of canopy extinction coefficient (k) of cumin under non-stress conditions for data combined over two sowing dates (GAI = green area index, $(1 - I/I_0)$ = fractional radiation interception, where I_0 is the incident radiation at the top of the canopy and I is the radiation transmitted by the green canopy).

3.4. Dry matter production

CUMMOD could simulate DM production with RMSD = 39.42 g m^{-2} (Fig. 6). The regression line between observed and predicted values for the test experiment showed that the model tended to under-predict DM production (Fig. 6a–b), as the slope of the regressed line was 0.71. This bias reduced when evaluation was done for seed yield (RMSD = 236.5 kg ha^{-1}). In the test experiment, seed yield was about 750 kg ha^{-1}, but simulated seed yield was around 840 kg ha^{-1}.

3.5. Potential yield and yield gap of cumin

Results showed that potential yield varied in different climatic conditions (areas with a cooler climate and higher radiation had higher potential yields). The highest value for potential yield belonged to Bojnourd (3.17 ton ha^{-1}) (Fig. 7a). In addition, the yield gap varied considerably among regions (from 2.42 ton ha^{-1} in Bojnourd to 0.68 ton ha^{-1} in Sabzewar). Actual yield showed considerable variability around the mean value and farmers have not been able to reach potential yield. This was true for all regions. The skewed polygon in Fig. 7-b shows yield gap calculated for the

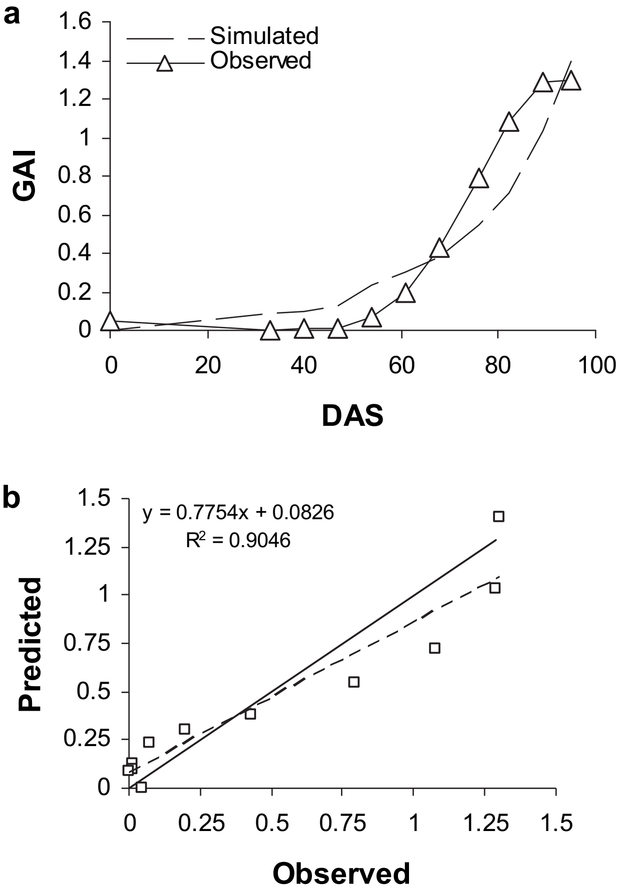

Fig. 4. Simulated against observed GAI based on observed data from Kafi (1989) and model run for year 1989 and sowing date of 28 February.

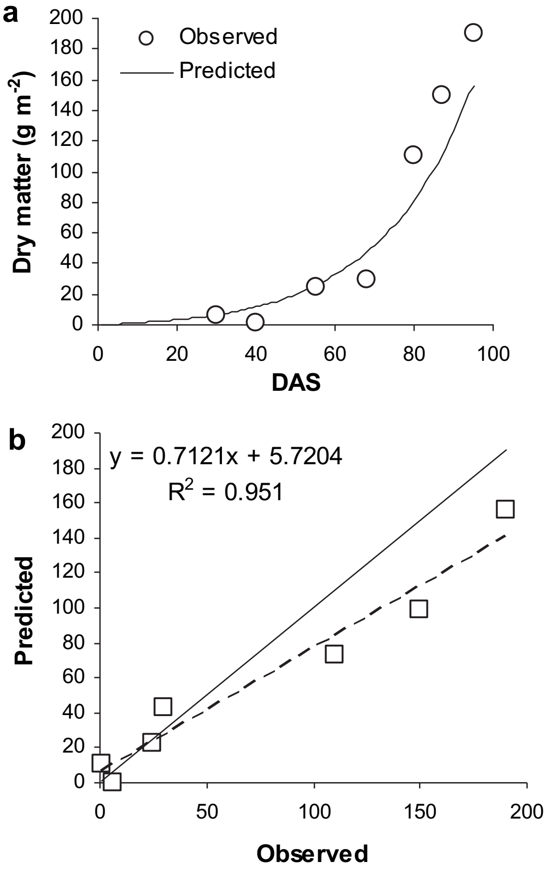

Fig. 6. (a) Observed and simulated dry matter; (b) Simulated against observed DM. Both base on observed data from Kafi (1989) and model run for year 1989 and sowing date of 28 February. DAS = days after sowing.

studied regions. As shown by the results, yield gap is greater in regions with a higher potential yield.

Multiple regressions with stepwise selection techniques are often used in ecology and in crop science for studying the effects of limiting factors on plant or animal characteristics such as plant biomass, species richness, or crop yield (Prost et al., 2008). Stepwise regression on yield gap as dependent variable and fungal infection, weed infestation, common practices, sowing date, salinity and successive planting as independent variables which affect yield gap show that fungal diseases, successive planting and sowing date could be used to interpret 73% of yield gap variation in 228 fields (data not shown). Also, our results indicated that 1% of the fungal infection increase equals to 150 kg per hectare yield loss. Therefore, these were considered as the main reducing or limiting factors in study regions with 38% contributed by fungal diseases, 30% by sowing date and 5% by successive planting. Lodha et al. (1986) also reported that losses due to wilt (*Fusarium oxysporum* Schl. f. sp. *cumini* Prasad and Patel) alone may reach 40%.

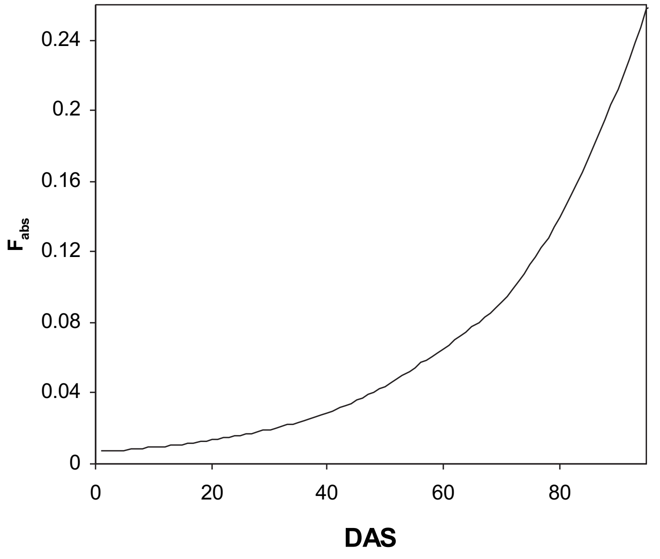

Fig. 5. Fraction of absorbed radiation (F_{abs}) based on model run for year 1989 and sowing date of 28 February. DAS = days after sowing.

Fungal diseases upon unawares and sometimes fail fields completely. Champawat (1990), in a two-year experiment to screen 161 cumin germplasms against *F. oxysporum* f. *sp cumini*, showed that among them four and three germplasms were semi-tolerant and sensitive, respectively, while the remainder were hypersensitive. Results showed that *F. oxysporum* and *Alternaria burnsii* were the most important fungal diseases that reduced cumin yield in the studied regions. Disease data showed that 67% of surveyed fields (averaged for all fields) were infected with both diseases. Our results showed that the percentage of infected fields to both fungal diseases (simultaneous infection) changed with latitude and infection increased with increasing latitude and tended to increase when moving from warmer and dryer to cooler and wetter regions (Fig. 8). Infection percentage in Gonabad and Ferdous (lower latitudes) was 47 and 40% respectively, while infection was 78 and 89% in Neishabour and Sabzewar (higher latitudes), respectively.

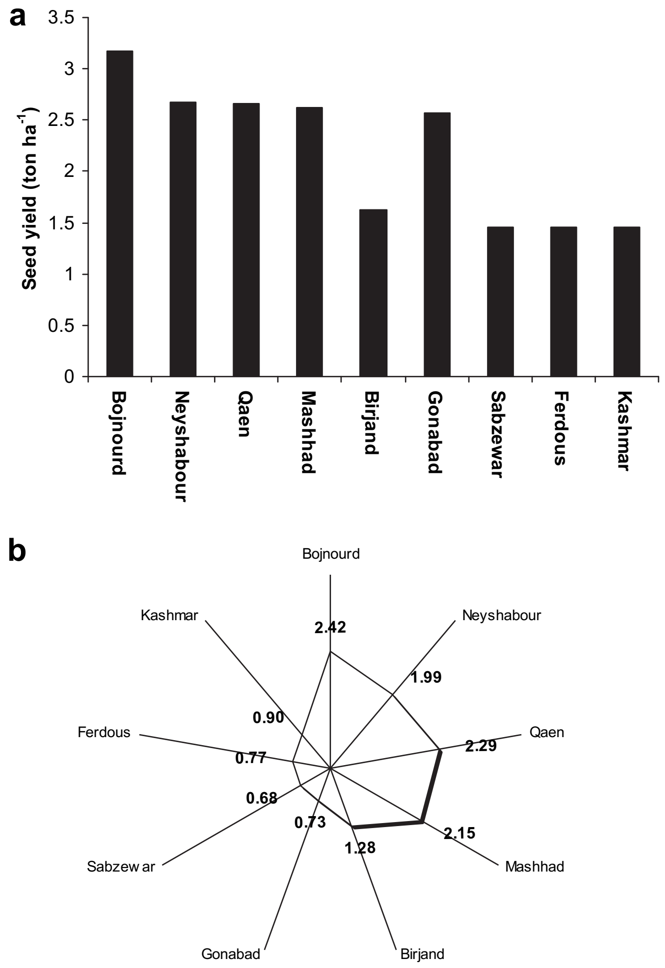

Fig. 7. (a) Potential seed yield of cumin by CUMMOD; (b) cumin yield gap calculated by potential yield subtracted with mean actual yield in all studied regions.

Infected fields to one of these fungal diseases (not both of them) showed that the prevalence of *F. oxysporum* increased at higher latitudes, but decreased for *A. burnsii* when moving to higher latitudes.

Alternaria is an air-borne fungus that appears in the first or last developmental stages of plants. Generally, it appears after flowering and infects the tissues with low sugar content (Gemawat, 1971a). In contrast, *F. oxysporum* is an anamorphic species with considerable morphological and physiological variation. Most of the interest in this fungus arises because of its ability to cause diseases in economically important crop hosts, but its near ubiquity in soil worldwide and its ecological activities indicate a much more diverse role in nature (Alves-Santos et al., 2007). This fungus is soil-inhabiting and is affected by soil moisture content during its life cycle.

The increasing effect of soil moisture on Fusarium wilt has been reported previously (Cook and Papendick, 1972). Infection percentage data against long-term precipitation values (15–40 years, mm) in study regions show that with a 3-mm increment in precipitation, infection increased around 1% (data not shown). Therefore, it seems that soil condition is a key factor that determines *Fusarium* spp. distribution, while it cannot be a key factor for *Alternaria* spp., as an air-borne fungus. Therefore, at lower latitudes, with warmer climate and harsher environment, especially with high soil salinity and low soil moisture content, *Fusarium* cannot spread well and consequently decreases cumin yield drastically.

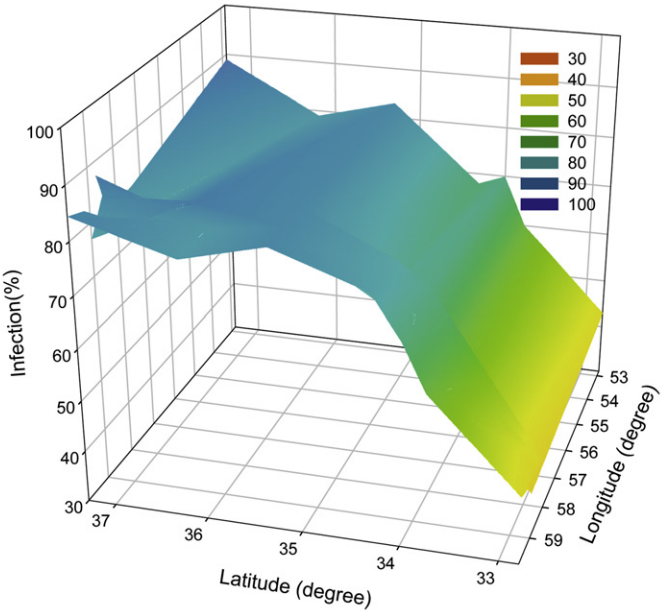

Fig. 8. Infection percentage of fields to *Fusarium oxysporum* in different latitudes and longitudes.

Gemawat (1971b) reported that optimum temperature for cumin blight (*Alternaria* spp.) varies from 23 to 28 °C, while 26–27 °C was reported by Uppal et al. (1938). Because this fungus infects cumin after flowering (Gemawat, 1971a), and its spread is enhanced after heavy irrigation or precipitation (Kafi, 2002), it can be seen in irrigated fields at lower latitudes.

Collected data shows that farmers are using a wide range of different sowing dates. Therefore, a sensitivity analysis was done by CUMMOD for sowing dates that varied from 1 October to 1 March (with 1-month intervals) to cover all possible sowing dates in each region (base on collected data from 228 fields). Sensitivity analysis on sowing date showed that in all regions, 1 December and 1 January were the best sowing dates, because the maximum seed yield was obtained with these dates. Our results were similar to another report (Rahimian Mashhadi, 1991), who showed that the best sowing dates for cumin in Mashhad were 9 December and 1 January (in that research sowing dates varied from December to March). Mollafilabi (1993) reported that when the sowing date was January, it was better than February in Qaen and Torbat-e-Jam (two regions in Khorasan provinces). Alavi (1969), with a series of experiments to study the effects of irrigation, fertilization, sowing date and seeding rate in Neishabour and Sabzevar, showed that shifting the sowing date from September to November reduced disease injury, but other treatments (seeding rate, N–P–K fertilizers application and seed disinfection with fungicides) had no effect on disease control. These results showed that in the range of common sowing dates, intermediate sowing dates were more favorable than early and late sowing dates. The collected data from studied fields and sensitivity analysis on sowing date (based on a range of common sowing dates) showed that inappropriate sowing date was one of the most important yield-reducing factors in all regions. Data showed that 63% of fields were not sown on the appropriate sowing dates (data not shown).

3.6. Assessment of the model

Quantitative data about cumin is scarce. Therefore, during this study, many important parameters were evaluated by timeconsuming and repeated measurements and a wide field survey of cultivated lands in Khorasan provinces, as the main production areas of Iran. Although a test of the model was not done using comprehensive experimental databases (due to the lack of data), it seems that this model can be used to preliminarily predict seed yield with an acceptable bias. Therefore, CUMMOD can be used to determine the capacity of regions to produce cumin and can be used to make decisions about spreading this crop to different regions and to provide cultivation maps. In addition, better evaluation of many parameters is required, especially temperature responses of cumin. In this model, it was presumed that cardinal temperatures of all phenological stages are the same, but there is an uncertainty with respect to this, and temperature should be evaluated separately for all phenological stages.

Simulated potential yield varied considerably among the regions. Different climatic conditions (in terms of temperature and solar radiation as main environmental driving variables) resulted in different potential yields (Fig. 7-a) because potential yield was higher in cooler regions with higher solar radiation and longer growing season. This has also been shown in other crops such as maize (Muchow and Kropff, 1997), wheat (Aggarwal and Kalra, 1994), soybean (Spaeth et al., 1987), and rice (Dingkuhn et al., 1995). High yield gap also showed that to minimize the gap and to optimize cultivated lands for growing cumin, the main factors that affect yield should be determined. Surveyed fields throughout Khorasan provinces (which extend from the North East to the South East of Iran) revealed that fungal diseases and inappropriate sowing dates are the main sources of yield gap variation in different fields.

Intermediate sowing dates are better than the early and late sowing dates. One of the most important reasons for reduced yield of cumin in late sowing dates is related to day length, because increased day length during spring days along with higher temperatures accelerated the development rate and shortened vegetative growth that resulted in lower GAI and consequently lower daily biomass production (data not shown). The effect of long days on yield reduction of cumin in late sowing dates and sensitivity of cumin to day length has also been reported in other studies (Rahimian Mashhadi, 1991; Kafi, 2002). Model outputs for intermediate sowing dates (1 December and 1 January) showed a higher fraction of radiation interception during the growing season than early and late sowing dates, because individuals subjected to short days during vegetative growth consequently experienced long spring days after achieving favorable GAI. On the other hand, in early sowing dates the crop experienced low radiation because incident solar radiation was lowest from October to December, while the canopy is ready to capture radiation. Since the canopy of cumin is considered to be weak, shorter vegetative growth also has an adverse effect on it, with lower GAI and fraction of absorbed radiation. High RUE (Fig. 3-a), but low radiation interception (Fig. 5) in this crop demonstrates that all factors affecting the fraction of absorbed radiation can also affect seed yield.

Fusarium oxysporum distribution as a soil-inhabiting fungus was attributed to greater soil moisture content, stems from more pronounced precipitation at higher latitudes (ranging from 261 mm in Bojnourd to 136.1 in Ferdous), and cooler climate, while unfavorable soils of lower latitudes (low soil moisture content and salinity) prohibit its distribution compared with higher latitudes. Higher temperature in lower latitudes and the air-borne nature of *Alternaria* spp. assist it to be distributed at lower latitudes. These results were consistent with other findings on fungal diseases prevalent in cumin (Kafi, 2002). In addition, field surveys showed that cumin has been cultivated successively at lower latitudes (e.g., more than 85% of fields in Ferdous), but continuous cultivation was seen in just 22 and 17% of Sabzewar and Neyshabour fields, respectively.

Our results show that despite the effect of other reducing factors on cumin yield in Khorasan provinces, designing proper cropping patterns and applying favorable rotations to alleviate the effects of fungal diseases and using appropriate sowing dates can decrease yield gap considerably (around 68%). Estimated potential yield in many regions (such as Bojnourd, Qaen, Mashhad and Neyshabour) by CUMMOD and comparison of results with actual yield obtained in 228 fields showed that if yield gap can be filled by appropriate management options (especially directing farmers to select the best sowing date and controlling fungal disease), yield can be increased by two- to four-fold in many regions (e.g., from 0.75 to 3.17 ton ha^{-1}) in Bojnourd with the greatest yield gap and from 0.77 to 1.45 ton ha^{-1} in Neyshabour with the least yield (ton ha^{-1}) (Fig. 7a). Using appropriate fungicides to disinfect seeds from seed-borne fungi and regulating irrigation schedules to maintain water content of soil within recommended doses can be considered as advisable management. Both sowing date and fungal diseases are related to water supply in the soil. Tavousi (2000) showed that in normal years with around 160 mm precipitation, additional irrigation is not necessary to produce cumin. Therefore, water supplied at more than 160 mm can be a cause of fungal infection in cumin fields of Khorasan provinces. Therefore, selection of appropriate sowing date can affect cumin yield by its indirect effect on water supply and consequently fungal infection.

4. Conclusions

Khorasan provinces can be considered as the center of excellence for special crops such as cumin. Cumin is an important spice crop of arid to semi-arid regions and its importance needs to be strengthened. To fill the yield gap of this crop, we suggest the following managements. (1) Intermediate sowing dates should be used in all regions. (2) Precise irrigation scheduling should be used for the regions of lower latitudes in the Razavi and South Khorasan provinces. (3) All possible managements should be taken to reduce damage by *Fusarium* spp. The disease control measures includes nutrient manipulation through amendments or modification of the soil environment (Engelhard, 1989), solarization, biocontrol (Chet et al., 1982), the application of metam-sodium (Frank et al., 1986), crop rotation (Katan et al., 1983), and application of three essential oils (cumin, basil and geranium) (Hashem et al., 2010). It should be mentioned that the first two options also are indirectly interrelated with the virulence of fungal diseases (as the main determinant-reducing factor on cumin yield gap), as intermediate sowing dates can help farmers to avoid from early heavy precipitation in Northern Khorasan fields and irrigation scheduling can help them to manage soil moisture content.

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