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ORIGINAL ARTICLE

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Forecasting of the flowering time for wild species observed at Guidonia, central Italy

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Abstract It is well known that forecasting the flowering time of wild vegetation is useful for various sectors of human activity, particularly for all agricultural practices. Therefore, continuing previous work by Cenci et al., we will present here three new phenoclimatic models of the flowering time for a set of wild species, based on an original data sample of flowering dates for more than 500 species, observed at Guidonia (42° N in central Italy) by Montelucci in the period 1960–1982. However, on applying the bootstrap technique to each species sample to check its basic statistical parameters, we found only about 200 to have data samples with an approximately Gaussian distribution. Eventually only 57 species (subdivided into eight monthly subsets from February to September) were used to formulate the models satisfactorily. The flowering date (represented by the *z* variable), is expressed in terms of two variables *x* and *y* by a nonlinear equation of the form $z=\alpha x^{\beta}+\gamma y$. The *x* variable represents either the degree-day sum (in model 1), or the daily-maximum-temperature sum (in model 2), or the daily-global-insolation sum (in model 3), while *y* for all three models corresponds to the rainy-day sum. Note that all summations involved in the computation of the variables *x* and *y* take place over a certain period of time (preceding the flowering phase), which is a parameter to be determined by the fitting procedure. This parameter, together with the threshold temperature (needed to compute the degree-days in model 1), represents the two implicit parameters of the process, thus the total number of parameters (including these last two) becomes respectively, five for model 1, and four for the other two models. The preliminary results of this work were reported at the XVI International Botanical Congress (1–7 August 1999, St. Louis, Missouri USA).

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Introduction

Early forecasting of the phenological phases of plant species is of great support to various sectors of human activity: agriculture (use of pesticide, choice of varieties), public health (allergies), tourism, the environment and monitoring climate changes. But the timely forecasting of the phenological stages of crops is mainly used for the rationalization of pesticide and fertilizer applications in relation to plant development and growth rate, thus allowing the environmental pollution resulting from agricultural practices to be reduced.

An evident limitation to this approach is the difficulty in finding a reference species close to the crops for which the phenological development has to be predicted; as reported by Robertson (1983), many factors, such as soil fertility, plant population, soil type, soil temperature and soil moisture, influence plant development.

Among the various phenological phases, the flowering time is the one most often considered, because it is easier to record and the ecological and physiological implications are simpler to interpret. Moreover, the environmental conditions during the flowering period of the plant and its sensitivity often have a considerable impact on the final yield of a crop; in fact, the quantity of pollen dispersed into the atmosphere during the flowering period of certain crops is a good indicator of the potential yield (Vossen 1994).

The flowering period is determined by complex interactions between genetic and environmental factors, the latter including rainfall, temperature and solar radiation, which exert a stronger effect than any other on vegetation development, especially the flowering phase, determining the most important year-to-year variations.

According to input data, the forecasting mathematical models can be distinguished as *phenological* or *phenoclimatic*.

The *phenological* models are based on the possible correlations between the phenophases of species other than that under consideration. These models are rather empirical and their construction requires a statistical

Table 1 Basic statistics (including bootstrap estimates of means, standard deviations and sample size) of the eight sub-samples (one for each month from February to September) of the beginning of flowering dates of the plant species used for determining the models. Note that the main sample includes more than 500 plant species observed at Guidonia (near Rome) in the period from 1960 to 1982. Only species with data having either an approximately normal distribution and bootstrap standard deviation less than an appropriate upper limit (which in general may be different according to the month) were taken into account. *ONo* order number in the main sample, *MFD* mean flowering dates, *BMFD* bootstrap mean of flowering dates, *SD* standard deviation, *BSD* bootstrap standard deviation, *MxFD* maximum flowering date, *MnFD* minimum flowering date, *SNo* number of sample data

ONo	Family	Species	MFD	BMFD	SD	BSD	MxFD	MnFD	SNo
February									
371	Oleaceae	*Fraxinus excelsior* L.	57.3	57.3	10.6	10.1	75	40	15
423	Ranunculaceae	*Anemone hortensis* L.	54.8	54.8	18.1	17.5	79	24	18
458	Rosaceae	*Prunus cerasifera* Ehrh. *var. pissardii* (Carriére) L.H.Bailey	55.0	55.0	12.3	12.0	72	32	23
461	Rosaceae	*Prunus domestica* L.	58.8	58.8	13.6	13.1	86	32	21
464	Rosaceae	*Prunus spinosa* L.	56.6	56.6	11.4	11.0	86	38	23
March									
3	Aceraceae	*Acer negundo* L.	70.5	70.6	9.4	9.1	83	53	22
32	Boraginaceae	*Myosotis arvensis* (L.) Hill	80.5	80.5	10.8	10.5	101	65	22
194	Geraniaceae	*Geranium molle* L.	81.2	81.2	10.7	10.3	104	61	22
254	Labiatae	*Ajuga reptans* L.	76.3	76.3	8.7	8.4	91	62	18
277	Lauraceae	*Laurus nobilis* L.	80.6	80.7	10.3	10.0	97	61	22
350	Liliaceae	*Muscari neglectum* Guss. ex Ten.	72.2	72.2	7.9	7.7	85	59	23
405	Plantaginaceae	*Plantago lanceolata* L.	73.2	73.1	10.4	10.1	94	52	23
449	Rosaceae	*Kerria japonica* (L.) D.C.	74.8	74.8	9.2	8.7	87	61	12
452	Rosaceae	*Pyrus comunis* L.	74.2	74.2	8.7	8.1	90	59	11
492	Salicaceae	*Populus canadensis* Moench	73.2	73.2	6.8	6.4	83	64	12
April									
40	Caprifoliaceae	*Lonicera fragrantissima* Lindley et Paxton	107.1	107.1	6.4	6.2	118	95	21
64	Celastraceae	*Euonymus europaeus* L.	109.6	109.7	9.6	9.2	123	90	17
107	Compositae	*Crepis vesicaria* L.	100.6	100.6	8.7	8.4	116	81	23
208	Gramineae	*Bromus hordeaceus* L.=*B. mollis* L.	110.4	110.4	6.9	6.7	121	98	19
316	Leguminosae	*Trifolium campestre* Schreber	108.4	108.4	8.6	8.4	123	93	23
340	Liliaceae	*Allium triquetrum* L.	104.6	104.6	3.6	3.3	110	100	9
366	Moraceae	*Broussonetia papyrifera* (L.) Vent.	109.9	109.9	7.4	6.9	124	97	12
396	Papaveraceae	*Papaver rhoeas* L.	105.5	105.5	9.7	9.4	124	86	23
433	Ranunculaceae	*Ranunculus muricatus* L.	104.3	104.3	8.2	7.9	118	92	18
538	Umbelliferae	*Scandix pecten-veneris* L.	99.5	99.5	4.8	4.6	108	91	16
May									
39	Caprifoliaceae	*Lonicera etrusca* Santi	130.9	131.0	9.0	8.5	145	116	13
41	Caprifoliaceae	*Lonicera japonica* Thunb.	131.1	131.1	6.3	6.1	144	119	20
111	Compositae	*Galactites tomentosa* Moench	134.6	134.7	11.5	11.0	158	120	16
235	Hydrangeaceae	*Deutzia scabra* Thunb.	138.1	138.1	7.1	6.7	147	126	13
287	Leguminosae	*Galega officinalis* L.	136.1	136.1	8.9	8.5	151	122	14
331	Leguminosae	*Vicia villosa* subsp. *varia* (Host) Corb.	131.5	131.4	9.2	8.7	145	119	11
364	Malvaceae	*Malva sylvestris* L.	142.0	142.0	7.2	7.0	159	129	22
376	Oleaceae	*Jasminum officinale* L.	141.7	141.7	8.5	8.2	156	124	21
455	Rosaceae	*Potentilla reptans* L.	130.9	130.8	9.8	9.4	153	107	21
487	Rutaceae	*Citrus aurantium* L.	133.7	133.6	10.2	9.4	149	116	9
June									
22	Bignoniaceae	*Campsis radicans* Seem.	175.9	175.9	9.0	8.7	192	154	21
72	Compositae	*Andryala integrifolia* L.	176.9	176.9	7.3	6.9	192	167	15
180	Dipsacaceae	*Scabiosa atropurpurea* L.	175.1	175.0	9.0	8.5	187	159	12
232	Guttiferae	*Hypericum calycinum* L.	162.6	162.6	8.3	6.7	177	152	16
262	Labiatae	*Mentha pulegium* L.	178.8	178.8	7.8	7.2	194	163	12
361	Malvaceae	*Althaea rosea* L.	165.9	165.9	7.4	7.1	178	152	18
512	Scophulariaceae	*Verbascum blattaria* L.	165.0	165.0	10.1	9.8	185	148	22
514	Scophulariaceae	*Verbascum sinuatum* L.	174.2	174.2	7.8	7.5	192	154	22
527	Umbelliferae	*Ammi majus* L.	179.6	179.6	9.6	9.2	200	163	16
546	Verbenaceae	*Verbena officinalis* L.	171.5	171.5	8.4	8.0	190	156	18

Table 1 (continued)

ONo	Family	Species	MFD	BMFD	SD	BSD	MxFD	MnFD	SNo
July									
108	Compositae	*Cynara scolymus* L.	185.4	185.4	6.4	6.0	195	175	11
114	Compositae	*Inula conyza* D C.	210.5	210.5	15.2	14.2	232	187	10
314	Leguminosae	*Sophora japonica* L.	200.1	200.2	11.5	10.7	216	187	10
530	Umbelliferae	*Daucus carota* L.	181.5	181.5	15.3	14.7	208	150	18
August									
406	Plumbaginaceae	*Plumbago europaea* L.	238.3	238.3	8.1	7.8	254	225	19
416	Primulaceae	*Cyclamen hederifolium* Aiton	236.9	236.9	10.9	10.5	263	215	23
534	Umbelliferae	*Foeniculum vulgare* Miller subsp. *piperitum* (Ucria) Coutinho	215.3	215.3	9.2	8.8	234	201	20
September									
11	Amaryllidaceae	*Sternbergia lutea* (L.) Ker-Gawl.	255.8	255.8	5.3	5.1	264	247	18
75	Compositae	*Arthemisia alba* (Turra)	258.6	258.6	5.4	5.1	268	249	16
78	Compositae	*Aster ericoides* L.	264.4	264.3	6.3	5.8	275	251	11
112	Compositae	*Heliantus tuberosus* L.	256.7	256.7	7.2	6.9	271	241	20
508	Scophulariaceae	*Odontites verna* (Bellardi) Dumort	262.6	262.6	5.6	5.4	272	250	21

analysis of long series of observational data to identify the marker species (Lieth 1974; White 1979; Marletto and Sirotti 1993). The appearance of a given event in one or more marker species is used as an index (or evidence) for its appearance in the objective species also.

On the other hand, the *phenoclimatic* models are based on the assumed relationships between the phenological phases of the involved species and the behaviour of the various meteo-climatological quantities, such as rainfall, temperature, humidity, insolation, etc. (White 1979; Castonguay et al. 1984; Oger and Glibert 1989; Marletto et al. 1992; Cenci et al. 1997).

Within this context, we will introduce three new phenoclimatic models involving the forecasting of the flowering dates of 57 wild species living at Guidonia near Rome (Italy).

Data and methods

The data base includes the dates for the beginning of flowering of more than 500 wild species observed at Guidonia near Rome (42° N in central Italy) between 1960 and 1982 by the late Prof. G. Montelucci (1899–1983), a naturalist and geobotanic in Rome.

All the meteorological data for the entire period (including the daily maximum and minimum temperature, daily rainfall, relative humidity and daily global insolation) come from the meteorological station of Guidonia.

In order to build the statistical models properly, for each species of the whole data sample, the main statistic (including the mean and standard deviation) was first checked by applying the bootstrap statistical technique. Owing to the brevity of the time series (only series involving up to 23 years of observations for each species were available), to satisfy the essential requirements of the statistical procedure involved in the analysis we could employ only a selected sample of about 200 species series, each having an approximately Gaussian distribution for their yearly flowering dates. Of these, only 57 species were effectively extracted pertaining to the eight monthly samples. Each has been interpreted by the three phenoclimatic models reported in this paper and critically discussed. The terminology of the species is that adopted by Pignatti (1982).

All such models could be expressed by the same formal equation $z=\alpha x^{\beta}+\gamma y$, i.e. the independent z variable (representing the flowering time) has been simply expressed in terms of a power relationship to the variable x and a linear dependence on the variable y. However, while for all three models the y variable is the rainy-day sum, the x variable represents the degree-day sum in model 1, or the maximum-daily-temperature sum in model 2, and finally the daily-insolation sum in model 3. Moreover, since for all three models both the x (it should also be noted that each term of the x variable in model 1 has to be over a certain threshold) and y variables involve a sum to be computed, starting from a certain date to be determined, the beginning date and the threshold temperature (this last only for model 1) were taken as two implicit parameters to be fitted. In order to represent the process mathematically with a sufficient degree of accuracy, an overall linear dependence on rainy days and a power explicit dependence on the thermal sums (degree-days or maximum daily temperatures for the model 1 or 2 respectively) or on the insolation sum (model 3) was required. However, we would like to point out remark that the flowering process is highly non-linear largely because of its implicit dependence either on the starting date (for models 2 and 3) or peculiarly on both the threshold temperature and the starting date (for model 1). Notwithstanding the brevity of the observational time series available for the analysis, the most relevant result of this work is the automatic estimate (with a determination of the statistical errors) of all fitted model parameters (including the implicit parameters also, i.e. the threshold temperature for model 1 and the starting date for the other models) by a maximum-likelihood method.

The best-fit parameter values and their uncertainties have been determined by the CERN (Geneva, Switzerland) MINUIT libraries. MINUIT is a system for minimizing a function of n parameters and computing the parameter errors and correlations. The errors (standard deviations) were determined by MINOS, a routine for non-linear error analysis of MINUIT. MINOS errors may be expensive to calculate, but are very reliable since they take into account both parameter correlations and non-linearities in the problem, and are in general asymmetric. As far as the final error in mean flowering date (z variable) is concerned, for each model we may consider the normalized frequency distribution of all its possible values, which can be computed by varying, in every possible way, the parameters of the model around their best estimates, within the standard error interval. The width of the best-fitted Gaussian curve of their distribution or its width at half height may be assumed as a reasonable estimate of the propagation error. But this procedure, in spite of its accuracy, is much time-consuming, therefore in common practice a good estimate of the RMS error of

Table 2 Comparison between the mean observed flowering dates (*MFD*) and those predicted (*z* variable) from each model. The estimated mean, *x*, and *y* values for various species are also displayed for each month. Model 1 (besides the starting date, STD) also involves a fourth parameter, the threshold temperature (T_{Thr}), which is shown. While the equation of the model takes the same form in all three cases, i.e. $z=\alpha x^{\beta}+\gamma y$, the *x* variable represents a different quantity depending on the model involved. For model 1 the *x* variable represents the thermal summation (degree-days) counted from a starting date and only including those days with mean daily temperatures above a given threshold. Analogously, for model 2 the *x* variable represents the maximum-daily-temperature summation (°C), while in model 3 it represents the global-insolation summation (langley-day), for both cases computed from a determinated date. For all three models the *y* variable represents the number of days with a precipitation greater than 1 mm, counted from the same starting date as for the *x* variable. Note that the starting dates and the threshold temperature (this last only enters into model 1) are implicit parameters of the models, which have to be determined for each sample considered

February

ONo	Family	Species	MFD	Model 1: STD=27±1 days, α=10.47±2.13[a], β=0.306±0.040, γ=0.61±0.22, T_{Thr}=1°C			Model 2: STD=27±1 days, α=7.28±1.73[a], β=0.342±0.040, γ=0.58±0.20			Model 3: STD=27±1 days, α=1.71±0.60, β=0.403±0.040, γ=0.52±0.20		
				x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
371	Oleaceae	*Fraxinus excelsior* L.	57	205	9	59	344	9	59	5077	10	59
423	Ranunculaceae	*Anemone hortensis* L.	55	199	7	57	336	7	57	5133	8	58
458	Rosaceae	*Prunus cerasifera* Ehrh. *var. pissardii* (Carriére) L.H.Bailey	55	184	8	57	308	8	56	4564	9	56
461	Rosaceae	*Prunus domestica* L.	59	207	9	59	349	9	59	5267	10	59
464	Rosaceae	*Prunus spinosa* L.	57	192	9	58	325	9	58	4882	10	58

March

ONo	Family	Species	MFD	Model 1: STD=52±1 days, α=33.19±2.50, β=0.150±0.010, γ=0.76±0.14, T_{Thr}=2°C			Model 2: STD=52±1 days, α=25.57±2.20, β=0.180±0.016, γ=0.66±0.14			Model 3: STD=52±1 days, α=14.71±1.80, β=0.188±0.015, γ=0.56±0.14		
				x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
3	Aceraceae	*Acer negundo* L.	71	128	5	72	253	5	73	3854	5	72
32	Boraginaceae	*Myosotis arvensis* (L.) Hill	81	215	8	80	414	8	81	6687	8	81
194	Geraniaceae	*Geranium molle* L.	81	216	8	80	417	8	81	6815	8	82
254	Labiatae	*Ajuga reptans* L.	76	171	7	77	334	7	77	5205	7	77
277	Lauraceae	*Laurus nobilis* L.	81	219	8	81	417	8	81	6668	8	81
350	Liliaceae	*Muscari neglectum* Guss. ex Ten.	72	139	5	73	276	6	74	4242	5	73
405	Plantaginaceae	*Plantago lanceolata* L.	73	149	6	75	294	6	75	4597	6	75
449	Rosaceae	*Kerria japonica* (L.) D.C.	75	147	6	75	296	6	75	4709	6	75
452	Rosaceae	*Pyrus comunis* L.	74	162	6	76	318	6	76	4950	6	76
492	Salicaceae	*Populus canadensis* Moench	73	153	6	75	298	7	76	4552	6	75

April

ONo	Family	Species	MFD	Model 1: STD=80±1 days, α=41.38±2.40, β=0.162±0.011, γ=0.49±0.10, T_{Thr}=2°C			Model 2: STD=79±1 days, α=31.91±0.89, β=0.189±0.003, γ=0.44±0.07			Model 3: STD=78±1 days, α=15.72±1.80, β=0.206±0.012, γ=0.28±0.09		
				x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
40	Caprifoliaceae	*Lonicera fragrantissima* Lindley et Paxton	107	302	7	108	528	7	107	10220	8	108
64	Celastraceae	*Euonymus europaeus* L.	110	308	9	109	549	9	109	11022	9	109
107	Compositae	*Crepis vesicaria* L.	101	225	6	102	398	6	102	7737	6	101
208	Gramineae	*Bromus hordeaceus* L.=*B. mollis* L.	110	339	8	110	592	8	110	11503	8	110
316	Leguminosae	*Trifolium campestre* Schreber	108	309	9	109	541	9	109	10585	9	109
340	Liliaceae	*Allium triquetrum* L.	105	279	7	106	481	7	106	9009	8	105
366	Moraceae	*Broussonetia papyrifera* (L.) Vent.	110	342	8	110	591	8	110	11322	8	110
396	Papaveraceae	*Papaver rhoeas* L.	105	273	8	107	482	8	106	9512	8	106
433	Ranunculaceae	*Ranunculus muricatus* L.	104	261	7	105	458	7	105	8964	8	105
538	Umbelliferae	*Scandix pecten-veneris* L.	100	208	6	101	374	6	100	7291	6	100

Table 2 (continued)

May

ONo	Family	Species	MFD	Model 1: STD=104±2 days α=47.60±2.13 β=0.171±0.009 γ=0.43±0.09 T_{Thr}=2°C			Model 2: STD=105±1 days α=41.31±1.84 β=0.179±0.009 γ=0.44±0.09			Model 3: STD=93±1 days α=10.70±0.40 β=0.259±0.014 γ=0.21±0.08		
				x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
39	Caprifoliaceae	*Lonicera etrusca* Santi	131	364	6	133	599	6	132	15557	8	133
41	Caprifoliaceae	*Lonicera japonica* Thunb.	131	353	7	133	597	7	133	15131	10	131
111	Compositae	*Galactites tomentosa* Moench	135	392	9	136	649	9	136	17119	12	136
235	Hydrangeaceae	*Deutzia scabra* Thunb.	138	472	8	140	768	8	139	18936	11	139
287	Leguminosae	*Galega officinalis* L.	136	398	9	136	670	9	136	17535	13	137
331	Leguminosae	*Vicia villosa* subsp. . *varia* (Host) Corb	131	348	8	133	581	8	133	15532	11	133
364	Malvaceae	*Malva sylvestris* L.	142	509	9	142	837	9	142	20562	12	142
376	Oleaceae	*Jasminum officinale* L.	142	504	10	142	826	10	142	20360	13	142
455	Rosaceae	*Potentilla reptans* L.	131	345	8	133	574	8	132	15434	11	132
487	Rutaceae	*Citrus aurantium* L.	134	396	7	135	654	7	135	16917	10	135

June

ONo	Family	Species	MFD	Model 1: STD=121±1 days α=34.02±2.70 β=0.237±0.010 γ=0.37±0.13 T_{Thr}=2°C			Model 2: STD=122±2 days α=29.01±4.10 β=0.246±0.010 γ=0.38±0.10			Model 3: STD=114±1 days α=7.79±0.10[b] β=0.301±0.010 γ=0.24±0.10		
				x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
22	Bignoniaceae	*Campsis radicans* Seem.	176	931	11	176	1396	11	176	29566	13	176
72	Compositae	*Andryala integrifolia* L.	177	964	12	178	1441	11	177	30051	14	177
180	Dipsacaceae	*Scabiosa atropurpurea* L.	175	910	11	175	1364	11	175	29058	13	175
232	Guttiferae	*Hypericum calycinum* L.	163	665	9	162	1009	9	162	22671	12	163
262	Labiatae	*Mentha pulegium* L.	179	1029	11	180	1523	11	180	31293	13	179
361	Malvaceae	*Althaea rosea* L.	166	745	10	167	1120	10	167	24566	13	167
512	Scophulariaceae	*Verbascum blattaria* L.	165	721	10	165	1088	9	165	24006	12	165
514	Scophulariaceae	*Verbascum sinuatum* L.	180	1019	12	180	1519	12	180	31598	14	180
527	Umbelliferae	*Ammi majus* L.	172	851	11	172	1277	11	172	27282	13	172
546	Verbenaceae	*Verbena officinalis* L.	172	851	11	172	1277	11	172	27282	13	172

July

ONo	Family	Species	MFD	Model 1: STD=125±1 days α=25.61±4.10 β=0.281±0.020 γ=0.34±0.30 T_{Thr}=2°C			Model 2: STD=120±3 days α=17.37±4.01 β=0.314±0.0046 γ=0.47±0.25			Model 3: STD=126±1 days α=6.23±1.40 β=0.329±0.020 γ=0.21±0.28		
				x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
108	Compositae	*Cynara scolymus* L.	185	1048	13	186	1687	14	186	2934	12	186
114	Compositae	*Inula conyza* D C.	211	1562	14	208	2443	15	209	41919	13	201
314	Leguminosae	*Sophora japonica* L.	200	1424	12	202	2227	13	202	36962	12	201
530	Umbelliferae	*Daucus carota* L.	182	1001	11	183	1608	13	183	27564	11	182

the *z* variable can be made in terms of the model-parameter standard errors by the quadratic formula of error propagation (neglecting correlations).

The spatial plots were performed by the Microcal (California, USA) ORIGIN package.

3. Results

For each month, the type and species examined were selected according to the sample sizes available in that month and the behaviour of their basic statistical param-

Table 2 (continued)

August

ONo	Family	Species	MFD	Model 1: STD=176±3 days α=54.86±7.40 β=0.201±0.010 γ=0.53±0.23 T_{Thr}=2°C			Model 2: STD=177±3 days α=51.85±5.17[a] β=0.200±0.026 γ=0.53±0.30			Model 3: STD=145±2 days α=3.40±0.50[a] β=0.395±0.014[a] γ=0.13±0.18		
				x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
406	Plumbaginaceae	*Plumbago europaea* L.	239	1388	6	239	1957	6	239	45914	13	238
416	Primulaceae	*Cyclamen hederifolium* Aiton	237	1352	6	237	1910	6	238	45242	12	237
534	Umbelliferae	*Foeniculum vulgare* Miller subsp. *piperitum* (Ucria) Coutinho	215	876	4	217	1226	4	216	35563	10	215

September

ONo	Family	Species	MFD	Model 1: STD=217±1 days α=99.09±7.01 β=0.140±0.010 γ=0.57±0.12 T_{Thr}=2°C			Model 2: STD=198±1 days α=60.00±6.70 β=0.192±0.010 γ=0.48±0.10			Model 3:[c] STD=196±1 days α=13.23±0.10 β=0.290±0.001 γ=0.19±0.16		
				x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
11	Amaryllidaceae	*Sternbergia lutea* (L.) Ker-Gawl.	256	816	6	257	1772	8	256	26968	8	256
75	Compositae	*Arthemisia alba* (Turra)	259	875	5	259	1865	7	259	27947	8	259
78	Compositae	*Aster ericoides* L.	264	999	7	265	2051	9	265	29890	9	264
112	Compositae	*Heliantus tuberosus* L.	257	825	6	257	1790	7	257	27257	8	257
508	Scophulariaceae	*Odontites verna* (Bellardi) Dumort	263	936	7	262	1956	9	262	29318	9	263

[a] Mean of the two MINOS errors (positive and negative)
[b] Parabolic error (MINOS failed to determine errors)
[c] Note the existence in this case of another candidate solution with similar probability that could be still taken into account and has the following parameters: STD=213±2 days, α=34.60±7.50, β=0.200±0.002, γ=0.22±0.10

eters. For the monthly sample data involved, together with the order number in the main sample and the family and species names, some details of the basic statistical parameters are displayed in Table 1. A detailed comparison between the mean observed flowering dates (MFD) and those determined (*z* variable) from the three models developed for each monthly subset (from February to September) is reported in Table 2. For an overall view of the results, some pictorial spatial plots of the analyses of some monthly data samples (as a more significant example, the months of March, May and September are presented here) are shown in Figs. 1–3 respectively. In the captions of each figure, some more details of the sample data involved and the models' best-fitted parameters, together with their standard errors, are also reported.

As far as the model errors in the flowering time (*z* variable) are concerned, these are of the same order of magnitude as those of the original observational sample. As an example, Table 3 reports, for comparison, the results of the error computation for the data samples of March (model 1), May (model 1) and September (model 3) (Figs. 1–3), which were determined by applying both the more accurate procedure (including the three parameters α, β, and γ) and the more simplified procedure involving the quadratic formula for error propagation.

Notwithstanding the brevity the available time series and the high non-linearity of the flowering process (at least as far as the meteorological parameters involved in the models are concerned, mainly the starting date and threshold temperature (T_{Thr}) in model 1 or the starting date parameter by itself in models 2 and 3), all three models for each examined month (from February to September) achieved an overall best agreement with the observational data. The merits of these findings result from the robustness of the statistical method employed, together with the accurate selection of samples for the analyses of the monthly data, according to whether or not they assumed an approximately Gaussian distribution with a standard error possibly less than 10 days. The drastic cut of the initial sample size enabled all the statistical procedures to be applied correctly to determine the models, ensuring the accuracy of the results. The automatic estimate of all the involved parameters, including the beginning date and the best temperature threshold (needed for computing the degree-day sums in model 1), is noteworthy.

As far as the results for the different months and their respective models are concerned, the following may be observed. (a) In general, all three models fit reasonably well for all months. However, while models 1 or 2 are

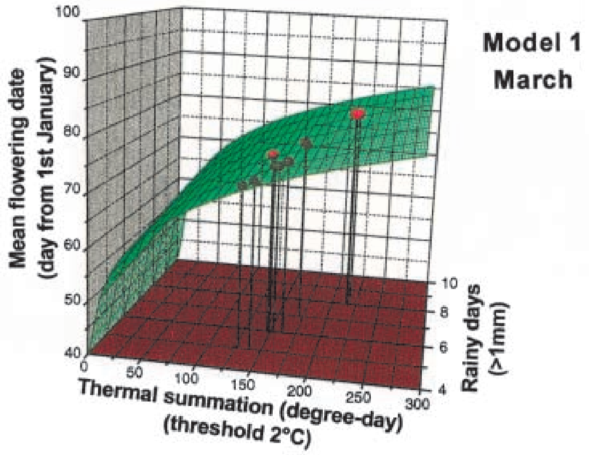

Fig. 1 Analysis of a data sample of flowering dates for 10 wild species observed at Guidonia (Italy) in the period from 1960 to 1982 (mean flowering date between 11 and 23 March and standard deviation <11 days), by using the model represented by equation $z=\alpha x^{\beta}+\gamma y$, where x is the thermal summations, y the number of rainy days and z the mean flowering date (model 1). The best model has the following parameter values: α=33.19±2.50, β=0.150±0.010, γ=0.76±0.14, T_{Thr}=2°C and beginning date 52±1 days from 1 January. The *bold dots* on the surface represent the observed mean flowering dates plotted against the x and y values, which were determined according to the beginning date estimated from the model

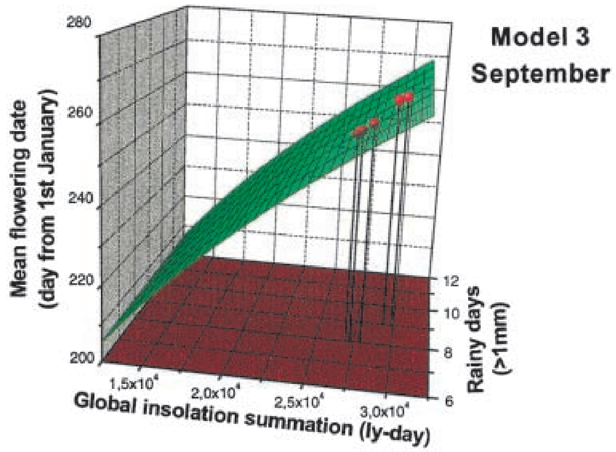

Fig. 3 Analysis of a data sample of flowering dates for 5 wild species observed at Guidonia (Italy) in the period from 1960 to 1982 (mean flowering date between 12 and 22 September and standard deviation <10 days), by using the model represented by equation $z=\alpha x^{\beta}+\gamma y$, where x is the global insolation summation, y the number of rainy days and z the mean flowering date (model 3). The best model has the following parameter values: α=13.23±0.10, β=0.290±0.001, γ=0.19±0.16 and beginning date 196±1 days from 1st January. The *bold dots* on the surface represent the observed mean flowering dates plotted against the x and y values, which were determined according to the beginning date estimated from the model

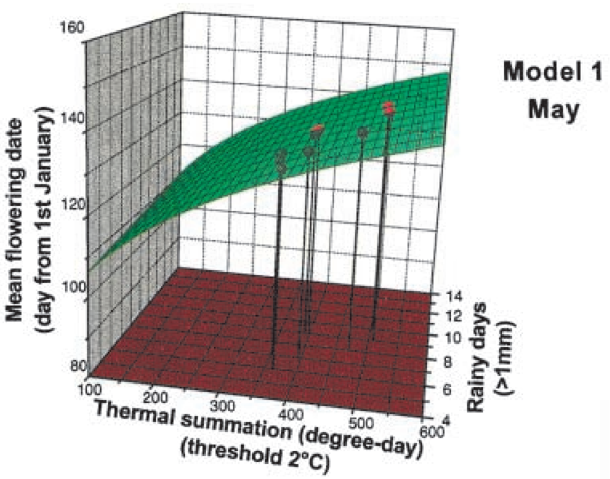

Fig. 2 Analysis of a data sample of flowering dates for 10 wild species observed at Guidonia (Italy) in the period from 1960 to 1982 (mean flowering date between 10 and 22 May and standard deviation <11 days), by using the model represented by the equation $z=\alpha x^{\beta}+\gamma y$, where x is the thermal summations, y the number of rainy days and z the mean flowering date (model 1). The best model has the following parameter values: α=47.60±2.13, β=0.171±0.009, γ=0.43±0.09, T_{Thr}=2°C and beginning date 104±2 days from 1 January. The *bold dots* on the surface represent the observed mean flowering dates plotted against the x and y values, which were determined according to the beginning date estimated from the model

more accurate than model 3 from February to May, their behaviour appears less satisfactory for the period from June to September, in which it seems that global insolation dominates the process. (b) As far as the threshold temperatures are concerned (model 1), they are 1°C for February, and 2°C otherwise. (c) The length of the development process (only small differences between the various models were found) for the species studied is of about 1 month in the period between February and May, and of more or less than 2 months from June to September. (d) The rainy days appear important in all the models for the months from February (where their contribution reaches the maximum) to June, but become irrelevant during July and August, particularly in model 3; in September they become relevant again for models 1 and 2, remaining irrelevant for model 3.

Conclusion

Finally, one may conclude that noticeable progress has been made in analysing the data and understanding the flowering process, building on previous work by Cenci et al. (1997), not only by the introduction of the bootstrap technique to check the main data-sample statistic, but chiefly by the completely automatic estimation of all the model parameters and their respective statistical errors, together with an initial attempt to estimate their specific relevance for determining the process during the different seasons.

Table 3 Comparison between the bootstrap observational errors and three different estimates of the propagated errors determined by the model equation. As an example, the three cases (plotted in Figs. 1–3) of model 1 (March and May) and of model 3 (September) are shown, where Δ'z, Δz'', and Δz''' represent the width of the fitted Gaussian curve of the error frequency distribution (determined by varying in every possible way the model parameters around their best estimates, within the standard error interval), its width at half height, and the error determined by the quadratic law of propagation respectively

March

ONo	Family	Species	MFD	BSD	Model 1 STD=52±1 days, α=33.19±2.50, β=0.150±0.010, γ=0.76±0.14, T_{Thr}=2°C					
					x	*y*	*z*	Δ'z	Δ''z	Δ'''z
3	Aceraceae	*Acer negundo* L.	71	9	128	5	72	8	9	6
32	Boraginaceae	*Myosotis arvensis* (L.) Hill	81	11	215	8	80	9	11	7
194	Geraniaceae	*Geranium molle* L.	81	10	216	8	80	9	11	7
254	Labiatae	*Ajuga reptans* L.	76	8	171	7	77	8	9	7
277	Lauraceae	*Laurus nobilis* L.	81	10	219	8	81	9	11	7
350	Liliaceae	*Muscari neglectum* Guss. ex Ten.	72	8	139	5	73	8	9	6
405	Plantaginaceae	*Plantago lanceolata* L.	73	10	149	6	75	8	9	7
449	Rosaceae	*Kerria japonica* (L.) D.C.	75	9	147	6	75	8	9	7
452	Rosaceae	*Pyrus comunis* L.	74	8	162	6	76	8	9	7
492	Salicaceae	*Populus canadensis* Moench	73	6	153	6	75	8	9	7

May

ONo	Family	Species	MFD	BSD	Model 1 STD=104±2 days, α=47.60±2.13, β=0.171±0.009, γ=0.43±0.09, T_{Thr}=2°C					
					x	*y*	*z*	Δ'z	Δ''z	Δ'''z
39	Caprifoliaceae	*Lonicera etrusca* Santi	131	9	364	6	133	11	13	9
41	Caprifoliaceae	*Lonicera japonica* Thunb.	131	6	353	7	133	11	13	9
111	Compositae	*Galactites tomentosa* Moench	135	11	392	9	136	12	14	9
235	Hydrangeaceae	*Deutzia scabra* Thunb.	138	7	472	8	140	12	14	10
287	Leguminosae	*Galega officinalis* L.	136	9	398	9	136	12	14	9
331	Leguminosae	*Vicia villosa* subsp. *varia* (Host) Corb.	131	9	348	8	133	11	13	9
364	Malvaceae	*Malva sylvestris* L.	142	7	509	9	142	13	15	10
376	Oleaceae	*Jasminum officinale* L.	142	8	504	10	142	13	15	10
455	Rosaceae	*Potentilla reptans* L.	131	9	345	8	133	11	13	9
487	Rutaceae	*Citrus aurantium* L.	134	9	396	7	135	12	14	9

September

ONo	Family	Species	MFD	BSD	Model 3: STD=196±1 days, α=13.23±0.10, β=0.290±0.0091, γ=0.19±0.16					
					x	*y*	*z*	Δ'z	Δ''z	Δ'''z
11	Amaryllidaceae	*Sternbergia lutea* (L.) Ker-Gawl.	256	5	26968	8	256	4	5	3
75	Compositae	*Arthemisia alba* (Turra)	259	5	27947	8	259	4	5	4
78	Compositae	*Aster ericoides* L.	264	6	29890	9	264	5	6	4
112	Compositae	*Heliantus tuberosus* L.	257	7	27257	8	257	4	5	4
508	Scophulariaceae	*Odontites verna* (Bellardi) Dumort	263	5	29318	9	263	5	6	4

Finally, it should be noted that the formal equation explored in this work to represent the flowering process of a particular set of wild species observed at Guidonia (central Italy), could be powerfully extended and applied to other places and plant species, provided that a sufficiently long time series of flowering dates and the main meteorological parameters (temperature, insolation, rainy days, etc.) of the area involved were available.

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