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RESEARCH ARTICLE

Phenological behaviour of *Parthenium hysterophorus* in response to climatic variations according to the extended BBCH scale

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Abstract

Considering the importance of ecological and biological traits in imparting invasive success to the alien species, the phenological behaviour of an alien invasive weed *Parthenium hysterophorus* was documented according to the extended BBCH scale in four different seasons. A phenological calendar was prepared using both two- and three- digit coding system, precisely describing the developmental stages of the weed. The phenological documentation is further supplemented with the dates corresponding to a particular growth stage, pictures of the representative growth stages and meteorological data of all the four seasons. Results revealed that the phenology of the weed altered in response to the changing temperature and humidity conditions but no apparent climatic condition could inhibit its germination or flowering. However, the emergence of inflorescence was highly sensitive to the temperature/photoperiodic conditions. Variations in the phenological traits of *P. hysterophorus* with changing environmental conditions explain the acclimatisation potential of the weed permitting its vast spread in the non-native regions. Since the given phenological illustrations are accurate, unambiguous and coded as per an internationally recognised scale, they could be exploited for agronomic practices, weed management programmes, and research purposes.

Introduction

Phenology is a scientific discipline dealing with the dynamics of the periodic events in the life cycle of a species. In biological sciences, the core phenological research addresses the timing of switches between recurrent developmental or behavioural phases (Badeck *et al.*, 2004). Phenological dynamics is an outcome of the complex interactions between genetic and environmental factors (Ruml & Vulić, 2005). Being one of the reliable bio-indicators of global change, as proposed by European Environmental Agency (Menzel, 2013), phenological studies have received due attention in the recent decades. Inter-relating the phenological traits with environmental variables may supplement the research advancements in the field of climate change, biodiversity, agriculture and forestry.

Plant invasion, a key contemporary issue in the biological sciences, is closely inter-linked with phenology. Theories explaining the success of invasive exotic species suggest that phenology, directly or indirectly, regulates the phenomenon of invasion (Wolkovich & Cleland, 2014). An analysis of the traits associated with invasion revealed that the flowering and reproductive biology is significantly related with the invasion success (Küster *et al.*, 2008). Invasive species are far more opportunistic with better phenological sensitivity, by virtue of which they may alter their phenologies in response to the seasonal variations (Wilsey *et al.*, 2011; Fridley, 2012; Throop *et al.*, 2012). This allows certain species to expand their invasion range with the shifting of favourable growth conditions and others to adjust with the changing environment. Either way, they gain a competitive advantage

over the natives. Coming decades may witness more of such phenological shifts under the projected seasonal catastrophes resulting from global warming and climate change. Temperature dependent changes in the phenology of exotic species have recently been noticed in North America (Wolkovich *et al.*, 2013). It is, therefore, pertinent to explore the phenological patterns exhibited by invasive exotic species in order to predict their responses in the future scenario and to devise better management strategies for their mitigation.

BBCH (**B**iologische Bundesanstalt, **B**undessortenamt and **CH**emishe Industrie) scale is a simplified, standardised and widely accepted phenological coding system. It was first proposed by Bleiholder *et al.* (1989) to describe growth stages of the plants, taking into consideration the decimal code published by Zadoks *et al.* (1974). Later on, it was adopted by Lancashire *et al.* (1991) to design specific scales of some cultivated plants. More recently, Hack *et al.* (1992) and Hess *et al.* (1997) proposed an 'extended BBCH scale' for crop and weed species with necessary improvements. The scale is a systematic description of the entire life cycle of a plant using a two- or three- digit decimal code. First and the second digit of the two-digit code represents 'principal growth stages' (PGS) and 'secondary growth stages' (SGS), respectively, both described by ordinal numbers, 0 to 9. Principal growth stages explain the broad and long-term developmental processes, generally common to a specific group of plant species, whereas SGS correspond to the characteristic short-term developmental steps that may be specific for genera or species. Further, the three-digit code allows the introduction of intermediate 'mesostages' for a detailed and better interpretation of each growth stage (Hack *et al.*, 1992). The scale is being extensively used to describe the developmental stages of cultivated plants and weed species, since it was first proposed in 1989 (Meier *et al.*, 2009). Earlier, its use was limited to the agricultural purposes, but lately it is being exploited for tracing the phenology of invasive alien plants (Jaryan *et al.*, 2014). The BBCH scale has been recognised as a standard system for describing phenological stages of a plant by European Phenology Network (van Vliet *et al.*, 2003) and European and Mediterranean Plant Protection Organization (EPPO) (Meier *et al.*, 2009).

Parthenium hysterophorus L. (Asteraceae) is an obnoxious invasive weed indigenous to the tropical and subtropical Americas. It is posing a serious threat to the natural- and agro-ecosystems in more than 50 countries worldwide (Belgeri & Adkins, 2015), by virtue of its high reproductive ability, wide range of ecological adaptation and allelopathic properties (Kohli & Rani, 1994). It is a weed of nearly 42 crop species, including staple food crops, commercial crops, oil seed crops, vegetables and pulses (Shi *et al.*, 2015). Also, the invasion of *P. hysterophorus* has altered the vegetation patterns and soil nutrient composition of the grassland communities due to its allelopathic interference (Nigatu *et al.*, 2010; Timsina *et al.*, 2011). Recent studies reveal that the invasion potential of *P. hysterophorus* is expected to be increased under climate change scenario (Shrestha *et al.*, 2015). The recent reports of its occurrence from previously un-invaded countries (Mahmoud *et al.*, 2015) and possibility of its further spread in parts of southeast Asia, sub-Saharan Africa, temperate northern hemisphere and high elevation equatorial regions (McConnachie *et al.*, 2011; Kriticos *et al.*, 2015; Mainali *et al.*, 2015) shows that *P. hysterophorus* has a considerable potential for rapid adaptation with the changing environmental conditions. Thus, understanding the phenological behaviour of *P. hysterophorus* may help in tracking its establishment, proliferation and invasion in novel habitats as well as in deciding the management options. A study was therefore, planned with an objective of (a) documenting the phenological traits of *P. hysterophorus* according to BBCH scale, and (b) understanding the phenological responses of the weed with changing environmental conditions.

Materials and methods

Variations in the phenological traits of *P. hysterophorus* were studied under different climatic conditions. The study was divided into four seasons with respect to temperature (T) and relative humidity (RH), that is S1 (Low T high RH); S2 (High T low RH); S3 (High T high RH); S4 (Low T low RH). On the basis of required variations in T (°C) and RH (%), 4 months, December (12°C; 93.1%), May (30.3°C; 55%), July (30.2°C; 90.5%) and October (25.1°C; 57%) were selected representing S1, S2, S3 and S4, respectively.

The experiment was established under partially natural conditions of experimental dome in the Department of Botany, Panjab University, Chandigarh, India (30°45′38″N; 76°45′55″E; 348 m above sea level) during 2014–2016. Wildly growing stands of the weed in Panjab University campus served as the seed stock for the experiment after a short period of dry storage as suggested by Tamado *et al.* (2002). One hundred mature seeds [weight: 0.06 ± 0.005 g (df-4); percent viability: 94.35 ± 0.113 (df-4)] were sown in earthenware pots (diameter: 25 cm; depth: 22 cm) during S1, S2, S3 and S4. The pots were kept free from the growth of any other weed and maintained properly for water requirement.

After germination, 30 individuals were tagged for documenting the phenological stages, which were reduced to 10 after the appearance of inflorescence. Each individual was carefully observed and photographed at regular intervals. A phenological calendar for *P. hysterophorus* was

prepared according to the extended BBCH scale (Hack *et al.*, 1992; Hess *et al.*, 1997). When 50% of the tagged individuals reached a particular phenological stage, date corresponding to the given stage was recorded and presented as DAS (days after sowing) describing the n^{th} day after the seeds were sown. Data pertaining to daily temperature and relative humidity was obtained from India Meteorological Department, Chandigarh, India. Data for day length has been compiled from Chandigarh Tribune (daily newspaper) available online at http://epaper.tribuneindia.com/t/299.

Results

The phenology of *P. hysterophorus* was described using both two- and three-digit BBCH coding system (Table 1). Description was based on the external morphological traits that can be easily observed, counted or measured and can be presented in ordinal or percentage values. However, the major developmental stages of the plant did not proceed in the defined series and may be unsequential or coinciding. Wherever necessary, three-digit coding may be taken into consideration for a better understanding of the phenological stages. The pictorial representation of the significant growth stages has been provided in Fig. 1.

Life cycle began with the hypogeal germination of the seeds (achene, 1–3 mm long and 1–1.5 mm wide) (stage 000; Fig. 1) and emergence of seedling through the soil surface, as described by PGS 0 (germination). This process took place beneath the soil, hence cannot be photographed or recorded. During S1, seed germination is delayed and took 14 days, whereas during S2, S3 and S4, seeds germinated in 3–4 days. The percent germination recorded during S1, S2, S3 and S4 was 76%, 81%, 96% and 83%, respectively. The average temperature was 12°C and humidity was 93% during S1. S2 and S3 witnessed similar temperatures (30°C) but varying humidity levels (55% and 90%, respectively). During S4, the average temperature recorded was 25°C and humidity was 57% (Fig. 3).

Thereafter, PGS 1 (leaf development) described unfolding of the cotyledons (stage 100; Fig. 1) and the subsequent true leaves. A leaf was considered unfolded when it attained the length of 1 cm. The first pair of true leaves was simple, opposite and elliptical in shape (stage 101/102; Fig. 1), whereas the subsequent leaves were simple but alternate, highly pubescent and runcinate in shape with slightly or deeply lobed margins (stage 107; Fig. 1). During S2 and S3, the cotyledons unfolded 3–7 h after the plumule breaks through the soil surface, whereas in case of S1 and S4, it took 20–38 h for the cotyledons to unfold. A gap of maximum 20 days was observed in the emergence of subsequent leaves during S1. On the contrary, during S2, the minimum gap was recorded in the appearance of subsequent leaves, which was as little as a few hours in certain cases. Principal growth stage 1 was completed in 112 days during S1 and 24, 58 and 68 days during S2, S3 and S4, respectively (Fig. 2). The total number of true leaves produced also varied seasonally with S4 producing the maximum number of leaves [33.2 ± 4.80 (df-29)] and S2 producing the minimum [9.1 ± 2.11 (df-29)]. The PGS 1 experienced an average temperature of 19°C during S1, 22°C during S4 and 29–32°C during S2 and S3 (Fig. 3a). Humidity levels were high during S1 and S3 (81–83%), optimum during S4 (69%) and very low in case of S2 (39%) (Fig. 3b).

During the initial vegetative growth of the plant, the stem remained short and leaves adhered to the ground, thus forming a rosette (stage 301–309; Fig. 1). The weed may arrest its growth at this stage depending on the environmental conditions. This stage was represented by PGS 3 (rosette growth) and described in terms of percentage of maximum diameter attained. In this study, S1 and S4 witnessed the rosette formation with a maximum diameter of 35.2 ± 1.821 (df-29) cm and 43.2 ± 2.669 (df-29) cm, respectively. The duration of the stage was more in case of S4 (88 days) than S1 (52 days) (Fig. 2). The average temperature and humidity during S1 was 18°C and 78%, respectively, and during S4 was 17°C and 82%, respectively (Fig. 3).

On the onset of favourable climatic conditions, the plant resumed its vegetative and reproductive growth, latter preceding the former. Thus, the remaining developmental stages were overlapping and occurred concomitantly. Since the plant does not reproduce vegetatively, PGS 4 (vegetative propagation) was omitted.

End of the rosette growth was marked by emergence of inflorescence (capitulum/flower head with five ray florets and numerous disc florets, 5–8 mm in diameter) as described by PGS 5 (inflorescence emergence) (stage 501–505; Fig. 1). This stage was accompanied by PGS 2 (formation of side shoots) (stage 201–209; Fig. 1). Although, the main stem as well as the lateral and higher order branches terminated in a globular capitulum, it was observed that their elongation succeeded the appearance of inflorescence. In the beginning, primary inflorescence appeared in the form of a terminal capitulum, enclosed between the terminal leaf axils. As the terminal capitulum developed, main stem began to elongate and secondary inflorescences started appearing in the axils of the lower leaves of the stem, producing lateral branches. Similarly, with the development of secondary inflorescence, lateral branch elongated and produced higher order inflorescences and branches. Thus, the development of terminal capitulum was accompanied by production of

Table 1 BBCH scale for *P. hysterophorus* and DAS (days after sowing) recorded for a particular stage in S1, S2, S3 and S4

BBCH Scale			DAS (Days After Sowing)			
2 digit	3 digit	Description	S1	S2	S3	S4
		Principal growth stage 0: Germination				
00	000	Dry seed (achene)	0	0	0	0
01	001	Beginning of seed imbibition	–	–	–	–
03	003	Seed imbibition complete	–	–	–	–
05	005	Radicle emerged from seed	–	–	–	–
06	006	Elongation of radicle, formation of root hairs and lateral roots	–	–	–	–
07	007	Hypocotyl with cotyledons or shoot breaking through seed coat	–	–	–	–
08	008	Hypocotyl with cotyledons or shoot growing towards soil surface	–	–	–	–
09	009	Emergence: cotyledons break through soil surface	14	3	3	4
		Principal growth stage 1: Leaf development				
10	100	Cotyledons completely unfolded	15	3	3	5
11–12	101–102	First pair of true leaves unfolded	35	7	6	9
13	103	Third true leaf unfolded	54	11	11	12
14	104	Fourth true leaf unfolded	57	15	15	15
15	105	Fifth true leaf unfolded	67	16	18	18
16	106	Sixth true leaf unfolded, small rosette developed	75	18	21	22
17	107	Seventh true leaf unfolded	82	19	27	25
18	108	Eighth true leaf unfolded	86	23	30	30
19	109	Ninth true leaf unfolded	89	26	33	34
	110	Tenth true leaf unfolded	92	–	40	36
	111	Eleventh true leaf unfolded	95	–	49	39
	112	Twelfth true leaf unfolded	99	–	60	41
	113	Thirteenth true leaf unfolded	103	–	–	44
	114	Fourteenth true leaf unfolded	106	–	–	49
	115	Fifteenth true leaf unfolded	110	–	–	52
	116	Sixteenth true leaf unfolded	115	–	–	55
	117	Seventeenth true leaf unfolded	119	–	–	58
	118	Eighteenth true leaf unfolded	122	–	–	61
	119	Nineteenth true leaf unfolded, rosette enlarged	126	–	–	72
		Principal growth stage 2: Formation of side shoots				
21	201	First lateral branch on the main stem visible	132	32	74	169
22	202	Second lateral branch on the main stem visible	137	34	77	171
23	203	Third lateral branch on the main stem visible	146	37	79	175
24	204	Fourth lateral branch on the main stem visible	155	51	83	179
25	205	Fifth lateral branch on the main stem visible	168	57	95	198
26	206	Sixth lateral branch on the main stem visible	181	64	109	202
27	207	Seventh lateral branch on the main stem visible	195	77	136	227
28	208	Eighth lateral branch on the main stem visible	208	–	–	235
29	209	Ninth lateral branch on the main stem visible	220	–	–	244
	210	Tenth lateral branch on the main stem visible	–	–	–	249
	211	Eleventh lateral branch on the main stem visible	–	–	–	253
	212	Twelfth lateral branch on the main stem visible	–	–	–	255
		Principal growth stage 3: Rosette growth				
31	301	Rosette 10% of the maximum diameter	75	–	–	39
35	305	Rosette 50% of the maximum diameter	92	–	–	61
39	309	Maximum rosette diameter attained	126	–	–	126
		Principal growth stage 4: Vegetative propagation (omitted)				
		Principal growth stage 5: Inflorescence emergence				
51	501	Primary (terminal) inflorescence begins to appear, indistinguishable from the developing leaves	128	31	72	160
55	505	Capitulum clearly visible in the terminal leaf axils, beginning of stem elongation	129	32	74	161

Table 1 Continued

BBCH Scale			DAS (Days After Sowing)			
2 digit	3 digit	Description	S1	S2	S3	S4
59	509	Petals visible on the terminal capitulum	131	34	75	164
	5 N1	Secondary inflorescence begins to appear on n^{th} lateral branch	–	–	–	–
	5 N5	Capitulum clearly visible in the lateral leaf axils, branch elongated	–	–	–	–
	5 N9	Petals visible on the capitulum, higher order branches produced	–	–	–	–
		Principal growth stage 6: Flowering				
60	600	Terminal capitulum completely developed	139	38	81	173
61	601	Beginning of flowering: 10% of capitula developed	162	55	105	194
63	603	30% of capitula developed, maximum stem length achieved	183	66	119	215
65	605	Full flowering: 50% of capitula developed	192	81	137	232
67	607	Flowering finishing: majority of capitula developed	216	101	255	247
69	609	End of flowering	263	144	291	265
		Principal growth stage 7: Development of seeds				
71	701	Seeds begin to develop in the terminal flower head	141	45	85	175
79	709	Seeds completely developed in the terminal flower head	143	47	88	177
	7 N1	Seeds begin to develop in the flower head on n^{th} lateral branch	–	–	–	–
	7 N9	Seeds completely developed in the flower head on n^{th} lateral branch	–	–	–	–
		Principal growth stage 8: Ripening of seeds				
81	801	Seeds begin to ripen in the terminal flower head	143	48	89	179
89	809	Seeds fully ripened in the terminal flower head	144	49	91	180
	8 N1	Seeds begin to ripen in the flower head on n^{th} lateral branch	–	–	–	–
	8 N9	Seeds fully ripened in the flower head on n^{th} lateral branch	–	–	–	–
		Principal growth stage 9: Senescence				
97	907	Plant dead and dry	285	169	298	284

subsequent capitula progressively down the stem and lateral branches, in a basipetal manner producing more and more lateral and higher order branches. Thus, the events were found to be co-occurring and cannot be recorded separately. After prolonged rosette stage, inflorescence in S1 and S4 was emerged 128 and 160 DAS (days after sowing), respectively. On the other hand, the terminal capitulum was observed 31 and 72 DAS in case of S2 and S3 (Fig. 2). Temperature during PGS 5 varied between 23–29°C, and it played a crucial role in deciding the time of bolting (Fig. 3a). Humidity patterns (45–72%) varied between different seasons but did not seem to influence the emergence of inflorescence (Fig. 3b). Considering, the importance of photoperiodic phenomenon in initiation of flowering, the average day length (hh:mm:ss) was observed 7 days prior to the emergence of inflorescence, and it was recorded to be 13:13:22 during S1, 13:59:43 during S2, 12:08:24 during S3, and 11:40:21 during S4. It took 7–13 days for the capitulum to develop completely after its emergence, irrespective of the season.

PGS 6 (flowering) described the proportion of fully developed capitula, beginning with the terminal capitulum (stage 601–605; Fig. 1). A capitulum was considered fully developed when all the five ray-florets appeared. The entire plant development was taken into consideration for PGS 6 and the reproductive growth was measured in terms of capitula produced on the main stem and all the branches. This is because main stem/lateral branches produce a single capitulum and give rise to higher order branches. Ray florets and disc florets within a capitulum emerge simultaneously and cannot be differentiated. Therefore, rather than applying a 3-digit code separately for the main stem and lateral branches, a 2-digit code was used to describe flowering of the entire plant. The duration of PGS 6 was recorded to be the longest in S3 (211 days) with 1236.6 ± 92.88 (df-9) number of capitula produced (Fig. 2c). In case of S1, S2 and S4, this duration was shorter (93–125 days) and the number of capitula produced was 39–51% higher in the former than latter (Fig. 2). The PGS 7 (development of fruit) and PGS 8 (ripening or maturity of fruit and seed) were overlapping with PGS 6. As soon as the terminal capitulum became mature, it started developing seeds and so was the case with the subsequent capitula. Time taken by a fully developed capitulum in producing the seeds did not vary significantly among different seasons. Within

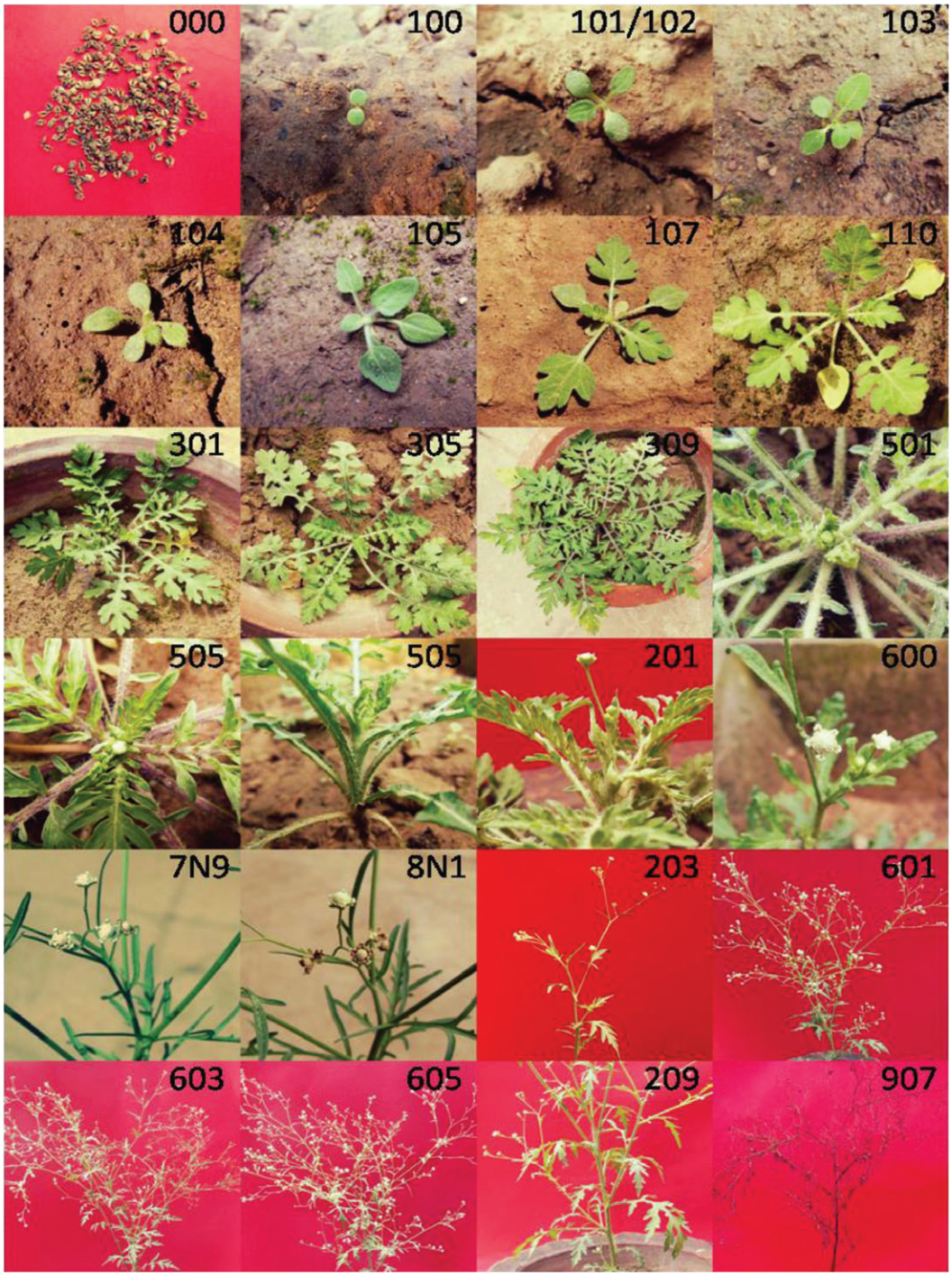

Figure 1 Significant growth stages observed in the life cycle of *P. hysterophorus*.

a very short period of time the seeds in the capitula developed, ripened (turned brown) and dispersed. In the meantime, elongation and branching of the main stem were also completed. The maximum plant height were achieved during S4 [62.4 ± 2.03 (df-9) cm], followed by S1 [48.14 ± 0.88 (df-9) cm], S3 [29.4 ± 1.03 (df-9) cm] and S2 [10.28 ± 0.278 (df-9) cm]. Similar pattern was observed for branching as well, with maximum number of branching in S4 [12.8 ± 0.08 (df-9)] and minimum in S2 [7.12 ± 0.19 (df-9)]. Principal growth stage

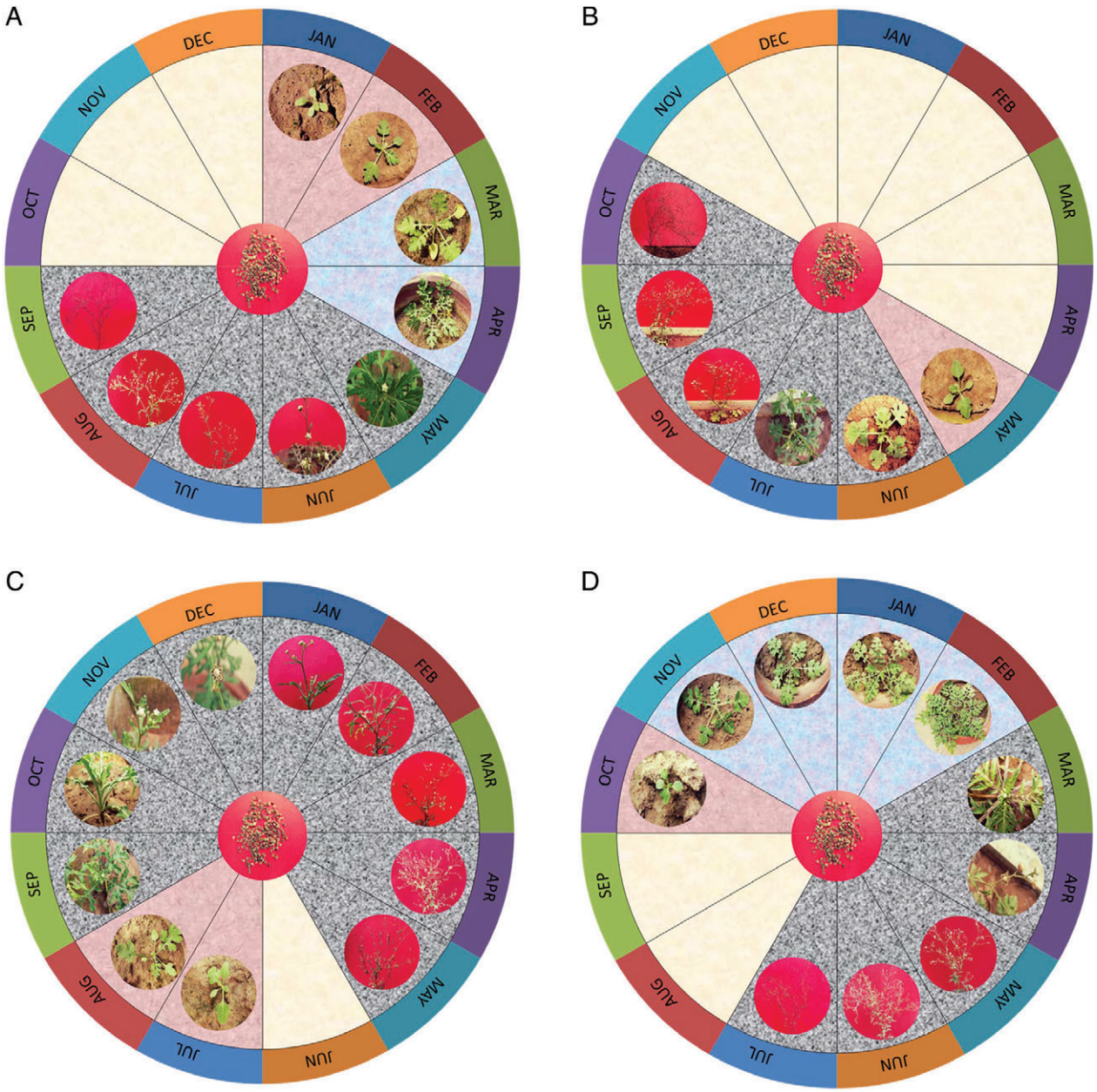

Figure 2 Variations in the life cycle of *P. hysterophorus* in S1 (A), S2 (B), S3 (C), and S4 (D).

6 continued for a very long duration and experienced an array of climatic conditions in all the four seasons. Principal growth stages 7 and 8, on the other hand, immediately followed the PGS 5 and therefore witnessed similar temperature and humidity levels. As more of the seeds were produced and ripened, vegetative growth decelerated and symptoms of senescence started appearing.

The final stage of the scale was represented by PGS 9 (senescence) when yellowing and drying of leaves, main stem and branches began from the base of the plant (stage 907; Fig. 1). Although the plant continuously shed the older leaves throughout its life cycle, however, at this stage, formation of new leaves impeded. Most of the capitula were dried and the seeds had been dispersed. With gradual reduction in the plant moisture content, main stem and its ramifications were completely dead. The average temperature (26–33°C) as well as humidity (38–74%) was variable during PGS 9 in all the four seasons (Fig. 3). The shortest life cycle was witnessed by S2 (169 days), whereas in other seasons it varied from 284

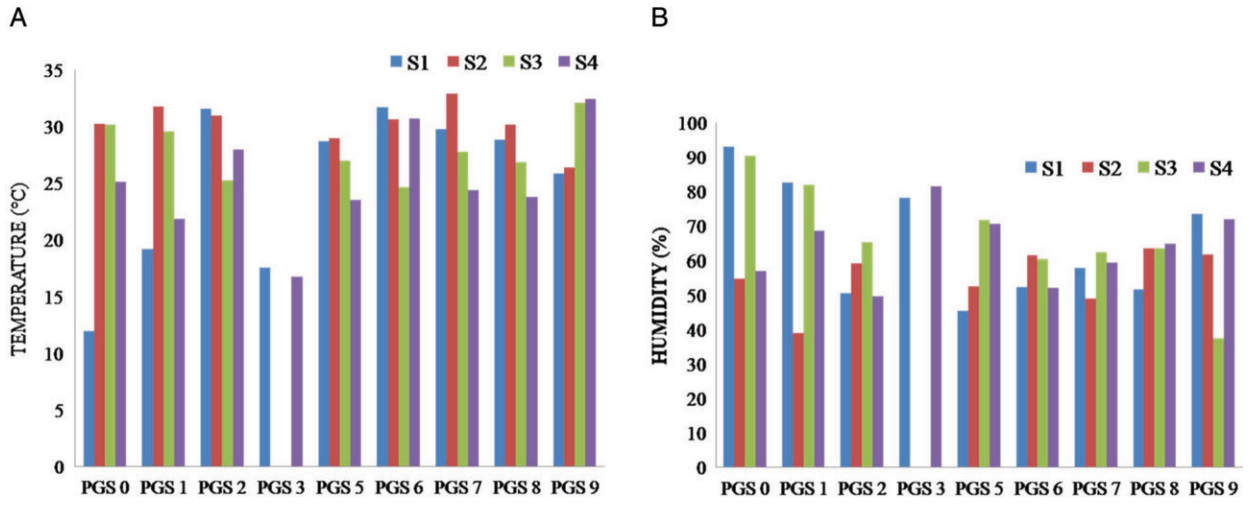

Figure 3 Average temperature (A) and average humidity (B) during different growth phases of *P. hysterophorus* in S1, S2, S3 and S4.

to 298 days. Vegetative phase was the longest in case of S4 (155 days), followed by S1 (113 days), S3 (69 days) and S2 (28 days). Reproductive phase, on the other hand, was the longest in S3 (228 days), followed by S1 (158 days), S2 (139 days) and S4 (125 days) (Fig. 2).

Discussion

The present study was conducted to demonstrate the acclimatisation potential of *P. hysterophorus* in response to the climatic variations. The duration of the life cycle varied with the changing environmental conditions, with an average life span being 9 months. Previous studies, however, reported that plant may complete its life cycle in an average of 5 months (Kushwaha & Maurya, 2012) or 7 months (Nguyen *et al.*, 2017). Batish *et al.* (2012) suggested that despite being an annual herbaceous weed, *P. hysterophorus* possesses a tendency to be perennial. However, during the given study, only a single flowering spell was observed in the entire lifetime of the weed and no perennial behaviour was noticed. Life cycle of the weed was completed within a year in all the four seasons, but in view of a prolonged reproductive phase during S3, it can be suggested that the life cycle may extend over a year, if more favourable environmental factors are present.

Vegetative phase was prolonged during S1 and S4 and short in case of S2 and S3, signifying the effect of climatic conditions on the length of vegetative period and initiation of the reproductive phase. Studies pertaining to the germination ecology of the weed revealed that no obvious climatic conditions can limit its germination (Tamado *et al.*, 2002). Present study has also witnessed that the germination of *P. hysterophorus* was not restricted to any particular season, but extremely low temperature conditions (12°C) delayed the germination of seeds during S1. Percent germination was highest during S3 which might be a result of combination of high temperature and high humidity conditions. Further, low temperature conditions (19–22°C) influenced the unfolding of cotyledons during S1 and S4 and the appearance of subsequent leaves during S1. The growth of the weed was suspended at the rosette stage during S1 and S4, as a strategy to escape the low temperature conditions (8–24°C). Earlier studies have also demonstrated that plants grown in the temperature regime 22/15°C stayed in rosette stage (Tho *et al.*, 2011). This attribute reflects its remarkable adaptability to survive in the harsh environmental conditions. On the contrary, the weed completed its vegetative growth rapidly under high temperatures (29–30°C), that is during S2 and S3. Low humidity conditions (39%) further shortened the vegetative phase in S2. In a similar study, it was observed that the warmer temperatures accelerated the growth of two Australian biotypes of *P. hysterophorus* and resulted in a shorter life span (Nguyen *et al.*, 2017). Earlier studies reported that the flowering of *P. hysterophorus* is usually insensitive to photoperiod and thermal regimes (Mahadevappa, 1997; Shabbir & Bajwa, 2006), but in the present study PGS 5 (inflorescence emergence) was identified as the most sensitive stage, responding strongly to the prevailing temperature/photoperiodic conditions. A study by Williams & Groves (1980) suggested that generally 13 h day light with warm temperature induces flowering in *P. hysterophorus*. Our results corroborate the given statement as flowering was observed only after an average temperature of 27°C and day length of 12:45:28 (hh:mm:ss).

Although, emergence of inflorescence required a threshold temperature (22–25°C), but once bolted, the

flowering may continue independent of the temperature and humidity. As a result, the weed can flourish luxuriantly throughout the year and this may provide a very strong competitive advantage over the native species. The average time interval between anthesis and seed shedding was 15 days, similar to that reported by Kushwaha & Maurya (2012). Reproductive phase of the weed continued for 4–8 months, thereby constituting the major part of its life cycle. Differences in the duration of reproductive phase were insignificant during all the seasons except for S3, where reproductive phase was exceptionally stretched. This could be a possible outcome of favourable growth conditions at the time of seed germination. Similarly, it was observed that the maximum plant height and highest number of branches was achieved in S4, followed by S1 which could be a result of prolonged vegetative phase during the initial developmental stages.

The study holds significant applications in the field of weed research and invasion biology. The periodicity of various events in response to the climatic conditions provides an estimation of the invasive potential of *P. hysterophorus*. It can be concluded that the optimum temperature and high humidity favours growth of the weed, but it holds the capacity to survive in any sort of climatic conditions. This observation is in accordance with a number of earlier studies (Batish *et al.*, 2012; Tho *et al.*, 2011; Kohli *et al.*, 2006; Tamado *et al.*, 2002). In order to escape the temperature or moisture stress, the weed either delays or paces up its reproductive growth. In the scenario of climate change, this adaptive behaviour of plant may prove beneficial. The present study supports the view that predicted increase in ambient temperature may enhance the growth and productivity of the weed as suggested by some recent studies, provided suitable moisture conditions are present (McConnachie *et al.*, 2011; Kriticos *et al.*, 2015; Bajwa *et al.*, 2016; Nguyen *et al.*, 2017). Description of the developmental stages in relation to time can also be utilised for comparing the patterns of phenology across native and introduced ranges (Jaryan *et al.*, 2014). More of such studies across temporal and spatial scales may acquaint the possible trends or shifts in the invasive behaviour of the plants in response to the environmental factors. In addition to this, the weak-links identified in the phenological behaviour of the weed can be exploited while designing the weed management programmes. In agricultural fields, herbicidal treatment is the most reliable strategy for the management of weeds. Since the success of herbicide treatment protocols depends on the correct timing of application, identification of most vulnerable growth stages may prove effective. In case of *P. hysterophorus*, weed management is needed at a pre-flowering stage in order to avoid its persistent seed banks in the soil. Studies revealed that most of the chemical treatments and biological control measures are more effective at the rosette stage (Khan *et al.*, 2012; Dhileepan, 2003). During high temperature conditions, the weed demands early control measures owing to its quick leap to the reproductive phase. Thus, a suitable period of treatment can be recognised, taking into consideration the annual life cycle of the weed and prevailing climatic conditions. Moreover, the phenological documentation is based on long-term observations and is coded as per a standardised scale therefore, can be utilised for further research purposes at an international level.

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References

Badeck F.W., Bondeau A., Böttcher K., Doktor D., Lucht W., Schaber J., Sitch S. (2004) Responses of spring phenology to climate change. *New Phytologist*, **162**, 295–309.

Bajwa A.A., Chauhan B.S., Adkins S.W. (2016) Morpho-physiological responses of two Australian biotypes of parthenium weed (*Parthenium hysterophorus* L.) to soil moisture stress. In *20th Australasian Weeds Conference*, Perth, Western Australia, September, Weeds Society of Western Australia, Australia, pp. 288–290.

Batish D.R., Kohli R.K., Singh H.P., Kaur G. (2012) Biology, ecology and spread of the invasive weed *Parthenium hysterophorus* in India. In *Invasive Alien Plants: An Ecological Appraisal for the Indian Subcontinent*, pp. 10–18. Ed. J.R. Bhatt, J.S. Singh, S.P. Singh, R.S. Tripathi, R.K. Kohli. Wallingford, Oxfordshire, UK: CAB International.

Belgeri A., Adkins S.W. (2015) Allelopathic potential of invasive parthenium weed (*Parthenium hysterophorus* L.) seedlings on grassland species in Australia. *Allelopathy Journal*, **36**, 1–14.

Bleiholder H., van den Boom T., Langelüddeke P., Stauss R. (1989) Einheitliche Codierung der phänologischen Stadien bei Kultur-und Schadpflanzen. *Gesunde Pflanzen*, **41**, 381–384.

Dhileepan K. (2003) Seasonal variation in the effectiveness of the leaf-feeding beetle *Zygogramma bicolorata* (Coleoptera: Chrysomelidae) and stem-galling moth *Epiblema strenuana* (Lepidoptera: Tortricidae) as biocontrol agents on the weed *Parthenium hysterophorus* (Asteraceae). *Bulletin of Entomological Research*, **93**, 393–401.

Fridley J.D. (2012) Extended leaf phenology and the autumn niche in deciduous forest invasions. *Nature*, **485**, 359–362.

Hack H., Bleiholder H., Buhr L., Meier U., Schnock-Fricke U., Weber E., Witzenberger A. (1992) Einheitliche Codierung

der phänologischen Entwicklungsstadien mono- und dikotyler Pflanzen. – Erweiterte BBCH-Skala, Allgemein. *Nachrichtenblatt des Deutschen Pflanzenschutzdienstes*, **44**, 265–270.

Hess M., Barralis G., Bleiholder H., Buhr L., Eggers T.H., Hack H., Stauss R. (1997) Use of the extended BBCH scale – general for the descriptions of the growth stages of mono- and dicotyledonous weed species. *Weed Research*, **37**, 433–441.

Jaryan V., Uniyal S.K., Gupta R.C., Singh R.D. (2014) Phenological documentation of an invasive species, *Sapium sebiferum* (L.) Roxb. *Environmental Monitoring and Assessment*, **186**, 4423–4429.

Khan H., Marwat K.B., Hassan G., Khan M.A. (2012) Chemical control of *Parthenium hysterophorus* L. at different growth stages in non-cropped area. *Pakistan Journal of Botany*, **44**, 1721–1726.

Kohli R.K., Rani D. (1994) *Parthenium hysterophorus*–a review. *Research Bulletin of the Panjab University, Science*, **44**, 105–149.

Kohli R.K., Batish D.R., Singh H.P., Dogra K.S. (2006) Status, invasiveness and environmental threats of three tropical American invasive weeds (*Parthenium hysterophorus* L., *Ageratum conyzoides* L., *Lantana camara* L.) in India. *Biological Invasions*, **8**, 1501–1510.

Kriticos D.J., Brunel S., Ota N., Fried G., Lansink A.G.O., Panetta F.D., Prasad T.R., Shabbir A., Yaacoby T. (2015) Downscaling pest risk analyses: identifying current and future potentially suitable habitats for *Parthenium hysterophorus* with particular reference to Europe and North Africa. *PLoS ONE*, **10**, e0132807.

Kushwaha V.B., Maurya S. (2012) Biological utilities of *Parthenium hysterophorus*. *Journal of Applied and Natural Science*, **4**, 137–143.

Küster E.C., Kühn I., Bruelheide H., Klotz S. (2008) Trait interactions help explain plant invasion success in the German flora. *Journal of Ecology*, **96**, 860–868.

Lancashire P.D., Bleiholder H., Boom T.V.D., Langelüddeke P., Stauss R., Weber E., Witzenberger A. (1991) A uniform decimal code for growth stages of crops and weeds. *Annals of Applied Biology*, **119**, 561–601.

Mahadevappa M. (1997) Ecology, distribution, menace and management of parthenium. In *Proceedings of the First International Conference on Parthenium Management*, October, University of Agricultural Sciences, Dharwad, India, pp. 1–12.

Mahmoud T., Gairola S., El-Keblawy A. (2015) *Parthenium hysterophorus* and *Bidens pilosa*, two new records to the invasive weed flora of the United Arab Emirates. *Journal on New Biological Reports*, **4**, 26–32.

Mainali K.P., Warren D.L., Dhileepan K., McConnachie A., Strathie L., Hassan G., Karki D., Shrestha B.B., Parmesan C. (2015) Projecting future expansion of invasive species: comparing and improving methodologies for species distribution modeling. *Global Change Biology*, **21**, 4464–4480.

McConnachie A.J., Strathie L.W., Mersie W., Gebrehiwot L., Zewdie K., Abdurehim A., Abrha B., Araya T., Asaregew F., Assefa F., Gebre-Tsadik R. (2011) Current and potential geographical distribution of the invasive plant *Parthenium hysterophorus* (Asteraceae) in eastern and southern Africa. *Weed Research*, **51**, 71–84.

Meier U., Bleiholder H., Buhr L., Feller C., Hack H., Heß M., Lancashire P.D., Schnock U., Stauß R., Van Den Boom T., Weber E. (2009) The BBCH system to coding the phenological growth stages of plants–history and publications. *Journal für Kulturpflanzen*, **61**, 41–52.

Menzel A. (2013) Plant phenological "fingerprints". In *Phenology: An Integrative Environmental Science*, 335–350. Ed. M.D. Schwartz. Dordrecht, The Netherlands: Springer.

Nguyen T., Bajwa A.A., Navie S., O'Donnell C., Adkins S. (2017) Parthenium weed (*Parthenium hysterophorus* L.) and climate change: the effect of CO_2 concentration, temperature, and water deficit on growth and reproduction of two biotypes. *Environmental Science and Pollution Research*, **24**, 10727–10739.

Nigatu L., Hassen A., Sharma J., Adkins S.W. (2010) Impact of *Parthenium hysterophorus* on grazing land communities in north-eastern Ethiopia. *Weed Biology and Management*, **10**, 143–152.

Ruml M., Vulić T. (2005) Importance of phenological observations and predictions in agriculture. *Journal of Agricultural Sciences, Belgrade*, **50**, 217–225.

Shabbir A., Bajwa R. (2006) Distribution of parthenium weed (*Parthenium hysterophorus* L.), an alien invasive weed species threatening the biodiversity of Islamabad. *Weed Biology and Management*, **6**, 89–95.

Shi B., Aslam Z., Adkins S. (2015) The invasive potential of *Parthenium* weed: a role for allelopathy. In *New Developments in Allelopathy Research*. Ed. J.E. Price. New York: Nova Science Publishers.

Shrestha B.B., Shabbir A., Adkins S.W. (2015) *Parthenium hysterophorus* in Nepal: a review of its weed status and possibilities for management. *Weed Research*, **55**, 132–144.

Tamado T., Schutz W., Milberg P. (2002) Germination ecology of the weed *Parthenium hysterophorus* in eastern Ethiopia. *Annals of Applied Biology*, **140**, 263–270.

Tho R., Hanan J., Dhileepan K., Shivas R.G., Adkins S.W. (2011) Simulation of parthenium weed canopy under changing climate using L-systems. In *19th International Congress on Modelling and Simulation*, December, Perth, Australia, pp. 1009–1015.

Throop H.L., Reichmann L.G., Sala O.E., Archer S.R. (2012) Response of dominant grass and shrub species to water manipulation: an ecophysiological basis for shrub invasion in a Chihuahuan Desert grassland. *Oecologia*, **169**, 373–383.

Timsina B., Shrestha B.B., Rokaya M.B., Münzbergová Z. (2011) Impact of *Parthenium hysterophorus* L. invasion on plant species composition and soil properties of grassland communities in Nepal. *Flora*, **206**, 233–240.

van Vliet A.J.H., de Groot R.S., Bellens Y., Braun P., Bruegger R., Bruns E., Clevers J., Estreguil C., Flechsig M., Jeanneret F., Maggi M. (2003) The European phenology network. *International Journal of Biometeorology*, **47**, 202–212.

Williams J.D., Groves R.H. (1980) The influence of temperature and photoperiod on growth and development of *Parthenium hysterophorus* L. *Weed Research*, **20**, 47–52.

Wilsey B.J., Daneshgar P.P., Polley H.W. (2011) Biodiversity, phenology and temporal niche differences between native- and novel exotic-dominated grasslands. *Perspectives in Plant Ecology, Evolution and Systematics*, **13**, 265–276.

Wolkovich E.M., Cleland E.E. (2014) Phenological niches and the future of invaded ecosystems with climate change. *AoB Plants*, **6**, plu013.

Wolkovich E.M., Davies T.J., Schaefer H., Cleland E.E., Cook B.I., Travers S.E., Willis C.G., Davis C.C. (2013) Temperature-dependent shifts in phenology contribute to the success of exotic species with climate change. *American Journal of Botany*, **100**, 1407–1421.

Zadoks J.C., Chang T.T., Konzak C.F. (1974) A decimal code for the growth stages of cereals. *Weed Research*, **14**, 415–421.