# 1. INTRODUCTION

Every single organism on the earth undergoes struggle for it's perpetuation and propagation. The fitter that emerge during the course of the struggle, try to dominate over the others in the process of resource sharing and in establishing the scope for their continued success in survival. However, besides the individual's ability or potential to win this race, the external factors involved also influence the result, to a considerable extent. Though the concept of categorising weeds and crops involve more of a human psychology than any botanical principle, from the point of view of agricultural production and food security, it is imperative that weeds or plants out of place deserve a control rather than co-existence. Control options are more constrained when plants are non-native with more of an invasive nature and complex biological adaptations. Such plant species or invasive alien plants need to climb up a series of steps or barriers to reach a new area and spread (Williams 2003). These steps could be consolidated as '5 E's. These 'E's are Entry/Escape, Establish, Expand, Explode and Entrench. These phases are often influenced by abiotic factors like climate. Such an interaction between the climatic conditions and the individual organism in the process of range extension that comprise the last '3 E's *viz*. Expansion, Explosion and Entrenchment could either be a direct impact or indirect impact. Triggering of biological traits of the species concerned could be considered as a direct impact. Removal of natural barriers or biotic factors that resist invasion by non-natives or aliens (through climate related disasters like flood or drought) could be the indirect effects of such interaction. However, the success of a particular species or weed in its invasive potential largely depends on such favour or resistance offered by climate, in the introduced range, as finishing with enthralling vigour and speed is more important than getting a good head start in any race or competition. Thereby, predicting weed invasiveness need to necessarily consider such of those climatic parameters that would alter their invasive traits. Predicting the process in reverse *i.e.* impact of changing climate on the invasive traits assume significance with the axiom 'Forewarned is Forearmed'. Many of the present age problematic invaders like *Prosopis juliflora* have caused serious inroads in to the cultivable fertile systems and thereby hinder their full potential towards realising food production. In this context it would be worthwhile to revisit the facts and concepts pertaining to the possible impact of climate change on the invasive traits of weeds.

**Process of Plant Invasion**

The process involves five phases (Williams 1997). Entry and spread of a weed species in a new geographic range has to tide over a series of physical barriers. Weed species that fail in this first phase in general do not acquire the status of quarantine pests by virtue of their dismal score in entry potential. If a species is successful in overcoming these barriers and gain entry in to a new range, the species passes through the phase of Entry/Escape and gets into the second phase of Establishment. In this phase, the weed species has to get through several abiotic and biotic stresses to establish itself in the new range. The species should be able to withstand, tolerate and come out of these biotic and abiotic stress with self sustaining populations, to establish itself, in the introduced/entered loci. Thereafter, these weed populations start expanding from this introduced loci to other surrounding habitats and this part of the process is the phase of Explosion, where the species concerned invades quickly large areas and several habitats. The last phase is the phase of Entrenchment, where the few left over habitats in the introduced range is being occupied by the weed and pattern of spread of the weeds starts plateauing, as the habitat range is saturated.

**Factors Favouring Invasion**

Fortunately, most introduced plants do not become invasive. Williamson's (1996) 'tens' rule of thumb of biological invasions suggests that only 10% of introduced species will become established in a host environment and that only 10% of the established invaders will become pests. The extent to which an introduced plant naturalizes and spreads depends on the suitability of the new physical, chemical and biological environment in which it finds itself. If these factors are unsuitable, the plant is unlikely to become established. If some aspects of the environment is unsuitable, the plant may persist until there is an environmental shift in its favour or perhaps until it evolves to meet the adverse condition. There are several examples of weeds undergoing such a lag phase after introduction, later becoming significant noxious weeds. A third requirement for establishment and spread of an introduced plant may be a suitable disturbance regime, which creates appropriate open niches for their invasion and naturalization.

**Genetic Variability**

Any weed introduced in to a new environment evolves in to a rapid invasive species, when the genetic variability is comparatively lesser. *Rubus alceifolius* with higher magnitude of genetic variability in it's native range (North Vietnam to Java) evolved itself as an invasive species in Madagascar with lesser genetic variability. This is a major weed in other Indian Ocean Islands, where its genetic variability is the least (Amsellem *et al*. 2000). Genetic introgression from *Rhododendron catawbiense* has been shown to impart cold tolerance on *R. ponticum*, a frequent invader in Britain and Ireland (Milne and Abbott 2000).

**Climatic and Edaphic Factors**

*Casuarina equisetifolia* has spread in California after the incidence of two hurricanes. In Cook Islands, the invasion of *Cardiosperunum grandiflorum* is reported to have been triggered by hurricane sally in 1986 (Meyer 2000). Flooding is an important factor contributing for the invasion of some species with hydrophytic adaptations like *Marsilea quadrifolia* in India. Disappearance of physical barriers such as rivers, roads and cliffs or a secondary human introduction favours invasion by asexually reproducing species such as *Selaginella* in East Africa (Binggelli 2000a).

**Biotic Factors**

It is observed that introduction of a pollinating agent *Parapristina verticillata* (a fig wasp) was responsible for the invasion of *Ficus microcarpa* in Florida, USA that was planted as an ornamental originally, 45 years before. This pollinator is also reported to be responsible for the spread of the species in New Zealand (Gardner and Early 1996). A shift in land use pattern in Hawaii from sheep grazing to cattle ranching allowed the shrub *Ulex europaeus* L. to invade. Cattle trampling resulted in microsites for seedling establishment. Cattle didn't graze on the species as effectively as sheep (Binggelli 2000 b).

Absence of natural enemies in the introduced range is another important factor contributing for the invasive potential of weeds as in the case of spread of *Eichhornia crassipes* in several parts of the world; invasion of *Acacia longifolia* in South Africa and *Chrysanthemoides monilifera* in Australia (Weiss and Milton 1984). Allelopathic potential of the invading species against the coinhabitants in the introduced range is another factor. Companion species of *Centaurea diffusa* in the native range have evolved resistance to these allelopathic aggression, stalling the predominance of *C. diffusa*. However, in the introduced range susceptibility of the companion species to this allelopathic potential allowed the weed *C. diffusa* to become invasive (Callaway and Aschehoug 2000). Interaction between the biotic factors and climatic factors might also encourage weed invasion. In Australia, the replacement of sheep by cattle coupled with frequent above average wet years favoured the invasion by (*Acacia nilotica* spp. Indica) (Tiver *et al.* 2001).

The fact that the process of invasion of a plant species is largely dependant on it's interaction with external factors whether biotic or abiotic, makes the need for observing the role of such factors on any potential invader, imperative to be forewarned.

## 2. IMPACT OF CLIMATIC PARAMETERS OF A LOCALITY ON WEED'S INVASIVE BEHAVIOUR

### Atmospheric Temperature

Invasive species whose native ranges are warmer than their introduced ranges would be at an advantage as they withstand hot temperatures better than natives of that region and as they suffer less mortality due to extreme cold conditions.

Increasing atmospheric temperatures could trigger invasion by some weeds in warm season crops. A rise in temperature by 3ºC of average temperature was shown to enhance biomass and leaf area of itch grass (*Rottboelliia cochinchinensis*) by 88% and 68%, respectively (Patterson *et al.* 1979). The weed has also been reported with projected increases in maximum growth for the middle Atlantic States (Patterson *et al.* 1999). This invasive weed causing significant yield reductions in sugarcane at Lousiana (Lencse and Griffin 1991) is also shown to be competitive in corn, cotton, soyabean, grain sorghum and rice systems (Lejeune *et al.* 1994). As many of these invasive weeds of southern U.S had their origin in areas associated with warm temperature of tropical climate, increasing temperatures might accelerate expansion of these weeds to northern states or region. (Patterson 1993). Increasing temperatures could also trigger northward migration of cogongrass (*Imperata cylindrica*) and witch weed (*Striga asiatica*) (Patterson 1995a). Increase in temperature due to global warming might trigger plant migration exceeding the rate of the same observed in post-glacial period (Malcom *et al.* 2002). This would lead to preferential selection of plant species with higher mobility. Plant traits that aid their dispersal over long distances are frequent in invasive plants (Rejmanek 1996). Accordingly, these invasive plants would be greatly triggered for migration by increasing temperatures (Dukes and Mooney 2000).

A hypothesis predicted migration of Kudzu (*Pueraria lobata* gaining entry to south eastern United States from Japan) to northern parts (Sasek and Strain 1990). The weed is shown to be restricted by low winter temperatures of -15ºC, two decades ago. Recent observations indicated midwestern populations of this weed and this migration is attributed to increase in minimum winter temperature (Ziska *et al.* 2010).

The impact of temperature changes on floristic composition is through tilting of balance towards crop in the process of crop weed competition. Crop losses due to weeds left uncontrolled are considerably higher in the south than in the north of U.S and this is attributed to the prescence of perennial invasive weeds like itch grass that are restricted in the northern states by low winter temperatures (Bunce and Ziska 2000). The crop-invasive weed competition could also be influenced by the varying magnitudes of response to the interaction of rising temperature and floral reproductive ability (Ziska and Reunion 2007).

In Australia, the increase in mean temperature is expected to be associated with range extension of tropical prickly acacia *A. nilotica* to south (Kriticos *et al.* 2003).

Higher mean annual temperatures are shown to favour assimilate partitioning towards root biomass in the introduced exotic species *P. juliflora*, in Southern India. Greater root biomass of this species aids rapid and robust regeneration after lopping of the shrub for the popular fuel wood purpose serving the livelihood of rural poor in the drier areas or after revival of ecological stress conditions such as drought or submergence (Kathiresan 2006a). Hyvonen *et al.* (2010) suggest climate change with particular reference to increasing temperature would increase the risk of population establishment of new weed species in northern regions of Europe. A definite warming trend in Germany is expected to increase the chances for the establishment of species with a higher temperature optimum such as *Vallisneria* species and those intolerant to freezing such as *P. stratiotes*, *Eichhornia crassipes* and *Salvinia auriculata* (Hussner *et al*. 2010).

**Soil Temperature**

Soil temperature plays a key role in promoting seed germination (Schonbeck and Egley 1980). Soil temperature could mainly serve the purpose of thermal induction of seed germination. Carpetweed *Trianthema portulacastrum* invading irrigated upland ecosystems in several tropical Asian countries is shown to be more invasive with synchronised mass seed germination, with increasing soil temperatures, in India (Kathiresan 2006b).

**Impact of Rainfall and Evaporation on Invasivity of Weeds**

Rainfall and evaporation pattern of a region influences the weeds directly by interrupting the physiological functions involved in the process of seed dormancy and germination and by imparting seed mortality due to excessive drying or soaking. These effects are transferred through soil moisture status. The indirect impacts could be through displacement of seeds / propagules by run off, scorching because of removal of soil cover and mobility of nutrients for better stand establishment.

**Soil Moisture**

Invasive weeds of rangelands like cheat grass (*Bromus tectorum*) and yellow star thistle (*Centaurea solstitialis* L.) depend largely on available soil moisture for seed germination. Prolonged or heavy winters that greatly enrich the soil moisture favour increased seed production of both the species (Patterson 1995 a). Interestingly, both species are also drought adapted. The adoption of cheatgrass for drought evadance is shorter life span whereas, deeper root system to endure drought helps star thistle, compared to other native species. Increase in snowfall or changes in snowfall variability is suggested to exacerbate the invasion of forbs in mixed-grass prairie ecosystem which in turn could influence the forage availability (Blumenthal *et al.* 2008). Soil moisture stress promoted greater herbivore tolerance for the invasive *Alternanthera philoxeroides* and decreased it for the native congener *A. sessilis* (Sun *et al.* 2010) in China.

**Pattern of Rainfall and Evaporation**

Global warming directly reflects on rising sea levels due to melting of ice caps and natural expansion of sea water as it becomes warmer. Consequently, areas adjoining the coast and wetlands could be frequently flooded and the distribution pattern of monsoon rains gets altered with more intense downpours, storms and hurricanes. On larger populations, precipitation extremes could tilt the weed-crop competition in favour of invasive weeds that would be reflected on declining crop productivity (Patterson 1995 b). The meteorological data available at the Annamalai University, in tail end of Cauveri river delta region of Tamil Nadu State, India, shows that the average annual rainfall during the last 20 years has increased by 233 mm compared to the average of previous 10 years (1588mm and 1355mm, respectively) while that of annual evaporation has come down by 453 mm (2153mm and 1700mm, respectively) (Table 1.). Phytosociological survey of floristic composition of weeds in this region reveals the recent invasion of the wetland rice fields by alien invasive weeds *Leptochloa chinensis* and *M. quadrifolia* (Table 2.). These two weed species dominated over the native weed such as *Echinochloa sp.* and others by virtue of their amphibious adaptation to alternating flooded and residual soil moisture conditions prevalent during recent years in this region (Yaduraju and Kathiresan 2003; Kathiresan 2005).

**Table 1. Rainfall and evaporation pattern in the Cauvery river delta region of India**

| Period | Annual Rainfall (mm) | Annual Evaporation (mm) | No. of wet years |
|---|---|---|---|
| 1980-1990 | 1355 | 2153 | 2 |
| 1990-2000 | 1483 | 1898 | 5 |
| 2000-2010 | 1588 | 1700 | 5 |

*L. chinensis* (Figure 1) owes it's invasive behaviour to longer life span that extends in to the relay crop of mung bean after transplanted rice. These two crops differ widely in the soil conditions with transplanted rice surviving in inundated water, whereas mung bean thrives in residual soil moisture below 30 per cent. *Leptochloa* shows adaptation to both the extremes of climate, with in the same generation. *M. quadrifolia* (Figure 2) is tolerant to most of the grass killer herbicides used like butachlor. Further, frequent floods do favour it's perpetuation.

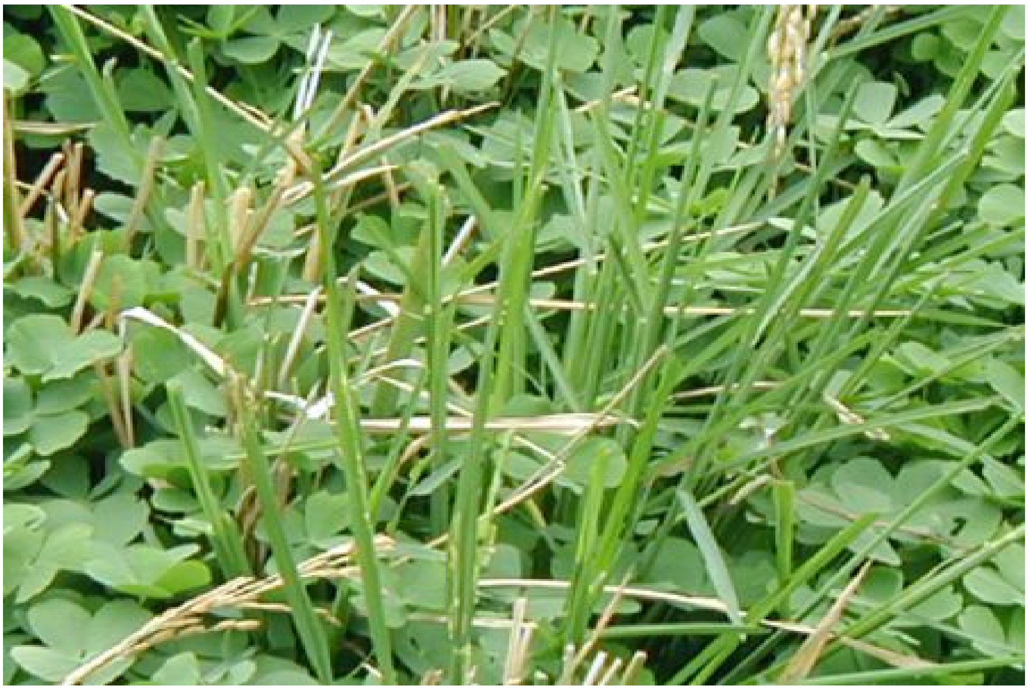
**Table 2. Floristic composition of weeds in rice fields irrigated by channels in Cauvery river delta (Importance Value Index %), India (Kathiresan 2011)**

| Weed species | Channel I | | Channel II | | Channel III | |
|---|---|---|---|---|---|---|
| | 1990 | 2010 | 1990 | 2010 | 1990 | 2010 |
| *Echinochloa sp.* | 25.56 | 7.93 | 28.48 | 8.01 | 27.52 | 4.02 |
| *Leptochloa chinensis* | 22.74 | 30.41 | 24.81 | 29.85 | 23.64 | 32.17 |
| *Cyperus rotundus* L. | 17.23 | 12.50 | 22.28 | 17.25 | 17.01 | 4.80 |
| *Sphenoclea zeylanica* | 2.02 | 6.28 | 0.68 | 2.17 | 1.68 | 7.24 |
| *Marsilea quadrifolia* | 1.46 | 39.61 | 0.63 | 41.84 | 0.46 | 40.32 |

Wetlands are more prone to weed invasions in part, because they serve as landscape sinks that accumulate materials resulting from both terrestrial and wetland disturbances (excess water, debris, nutrients, sediments, salts and other contaminants). Opportunities that make wetland more prone to weed invasions are that the riparian habitats are subjected to flood pulses and inflows from surface water. Habitats fed by surface water are low in species richness and the inhabitants are low in quality with co-efficient of conservatism scoring less than five. Studies in Wisconsin show that wetlands with a history of hydrological disturbance show more widespread invasions (Zedler and Kercher 2004). Despite the emphasis on increased influxes as causing disturbance, it has also been observed that some invasives are abundant where the regions have reduced flood flows. Both increased and decreased run off will alter wetland water regimes and the floristic composition could be invaded by the floating weeds, like *E. crassipes* under inundation and *Ipomoea aquatica* under semi or complete dry situation of water sheds in southern India (Kathiresan 2005). Grater spring-time moisture associated with El Nino events may trigger the range expansion of cheat grass (Bradley and Mustard 2005). Weeds constrained by rainfall such as *Eupatorium riparium* may expand if rainfall increases in some areas (McFayden 2008).

**Figure 1.** ***Leptochloa chinensis*** **in transplanted rice**

**Figure 2. Dominance of** ***Marsilea quadrifolia*** **due to flooding in low land rice**



Soil moisture status with available soil moisture percentage between 40 to 60 is observed to favour the seed germination of invasive weed *Parthenium hysterophorous*, whereas available soil moisture above 80 per cent coinciding with winter months or below 40 per cent coinciding peak summer is detrimental (Kathiresan *et al.* 2005). Soil moisture status is influenced by the rainfall as well as evaporation pattern of the microclimate concerned. The absence of or dismal rainfall (less than 30 mm) during March to May, coupled with higher rates of daily evaporation ranging from 4 to 8 mm a day, results in water deficit status of the microclimate during this part of the year, which ultimately reflects on depleting soil moisture status below 40 per cent.

In Australia, the seedling survival and growth is favoured by high soil moisture status whereas the seed germination is suppressed in *A. nilotica* (Kriticos *et al.* 2003). Inter annual amplified response to rainfall by non-native cheat grass (*B. tectorum*) dominating the ecosystems in the Great Basin, US is observed to be distinct from the native shrub *viz.* bunch grass (Bradley and Mustard 2005). Altered precipitation, increases in snowfall and variability of snowfall might exacerbate for invasion in the mixed grass prairie. Increased snow addition favours biomass production of *C. diffusa* and *Linaria paniculata* (Blumenthal *et al.* 2008)

Overall, altered pattern of precipitation with variable quantity and distribution pattern coupled with changes in evaporation pattern are likely to influence an array of biological traits of invasive weeds, including germination, plant size, seed production and distribution of water borne propagules.

**Elevated $CO_2$ Concentration**

Elevated $CO_2$ stimulated the invasive traits of non-native species than native species sympatric in the region, under controlled environmental conditions. The average E/A ratio (ratio of final biomass at elevated / ambient $CO_2$, when the $CO_2$ concentration is doubled) is inferred as 1.82 in non-native species where as it is 1.28 in native species (Sasek and Strain 1991).

Amongst great basin grasses the non-native *Bromus tectorum* showed a E/A ratio of 1.54 while native grasses recorded only 1.31 (Smith *et al.* 1987). This E/A ratio of non-native *Rhododendron ponticum* is reported as 1.59 against 1.12 in native under story plants of a Swiss forest (Hattenschwiller and Korner 2003).

The mechanisms that contribute for better response of invasive species to elevated $CO_2$ compared to native species have been reported as (i) plant architectural differences by virtue of leaf area (Sasek and Strain 1991; Huxman and Smith 2001; Ziska 2003) and (ii) altered reproductive allocation with particular reference to incorporation of carbon and nitrogen in seeds and increased differential abundance in community seed rain (Huxman *et al.* 1999; Smith *et al*. 2000).

Benefit of increased atmospheric $CO_2$ concentration is shown to increase the recruitment of five woody legumes *Acacia farnesiana*, *Gleditsia triacanthos, Leucaena leucocephala, Parkinsonia aculeata* and *Prosopis glandulosa* with greatest benefit to *Parkinsonia* and *Prosopis*. This is attributed to increased drought tolerance by virtue of enhanced seedling survivorship and by reduced grass depletion of soil moisture (Polley *et al*. 2002).

Stimulation of bio-mass production by 46% in response to a doubled $CO_2$ concentration by six different invasive species is reported (Ziska 2003). The response of these species (in terms of increased biomass) to the natural increase of atmospheric $CO_2$ by 30% during the $20^{th}$ century averaging 110% is significantly higher than the native species. This is construed as probable evidence to the fact that many plant invasions during the last century have been triggered by rising $CO_2$ levels. Besides increased branching and leaf area, higher pollen production from rag weed (*Ambrosia artemissifolia*) that is detrimental to human health (Ziska and Caulfield 2000) and higher spine production in *Cirsium avvense* (Ziska 2002) are also reported.

Response to elevated $CO_2$ by three invasive species *Mikania Mikrantha*, *Wedelia trilobata* and *Ipomea cairica* are compared with their native congeners *Paederia scandans, Wedelia chinensis* and *Ipomea pescaprae* by Song *et al*. (2009) in China. The average increase in photosynthetic rate in invasive species compared high of 67.1% against 24.8% in native species. Average increase of total biomass is also greater for invasive species (70.3%) than for natives (30.5%).

# 3. WEED TRAITS TO BE OBSERVED ON EXPOSURE TO VARIABLE CLIMATIC PARAMETERS, AS CONTRIBUTING FACTORS OF INVASIVITY

**Process of Seed Dormancy and Germination**

Dormancy is defined as an internal condition of the seed that impedes its germination under otherwise adequate hydric, thermal and gaseous conditions (BenechArnold *et al*. 2000). Seed dormancy is a complex mechanism that influences the time of emergence of a weed population. However, dormancy could not exclusively determine the persistence of the seed (Thompson *et al*. 2003). Seed dormancy is stated as a cryptobiotic state manifested by a particular form of cessation of growth (Suthar *et al*. 2009).

Seed characteristics such as dormancy from an individual plant can vary greatly depending on the mother plant and environmental conditions. This is because the seed coat is made from plant tissue of the mother plant and the environmental conditions during seed maturation influences the seed coat hardiness in *Medicago lupinalia* L. (Fenner and Thompson 2005). Soil temperature and water status play vital role in breaking dormancy and triggering germination (Sauer and Struik 1964). Exposure to light briefly during land preparation also triggers weed seed germination (Wesson and Wareing 1968). Two of the environmental changes that promote germination, involving light signals are observed as 1) soil disturbance by agricultural operations and 2) gap openings in dense canopies. In several species, exit from dormancy is completed only after the seeds have been exposed to fluctuating temperatures. Nine different parameters of diurnal temperature cycles are attributed for stimulating germination. They are, the number of cycles, their amplitude, maximum temperature, minimum temperature, duration of exposure under maximum temperature, duration of exposure to minimum temperature, rate of warming, rate of cooling, and the timing of the cycles regarding start of imbibition. Alteration in any of these without reflecting on at least one another is not possible. Evidences are also shown for the fact that not all of these characters have an active role. (BenechArnold *et al*. 2000). In *Chenopodium album*, breaking of dormancy response can increase from an amplitude of as little as 2.4ºC up to about 15ºC (Murdoch *et al*. 1989). Saturated soil moisture or flooding inhibited seed germination of Texas weed

(*Caperonia palustris*) and temperatures fluctuating between 30 / 40ºC is found to be optimum for germination (Koger *et al.* 2004).

Available soil moisture percentage above 60 per cent or below 40 per cent is deleterious for sprouting of *P. hysterophrus* seeds where as monthly average temperatures of above 34ºC is also detrimental (Kathiresan *et al*. 2005). Breaking of seed dormancy due to accumulated heat units and thermo induction of seed germination resulting in mass or synchronized weed germination and establishment is observed to be one of the key factors contributing for invasive ground cover of *T. portulacastrum* (Kathiresan 2006b). Increasing heat in the top soil due to increasing atmospheric temperature from 35ºC onwards during summer months of April, May and June triggered the mass germination and higher seedling emergence from June to August. Neutral pH is reported to be favourable for germination of *Solanum nigrum* (Suthar *et al*. 2009). While flooding of farm lands is observed to depress sprouting of seeds of old corn weed (*R. cochinchinesis*) it is also observed to trigger germination of fresh seeds (Oyewole and Ibikunle 2010).

**Seed Bank Longevity**

Germination and stand establishment is not imminent, once the weed seeds get dispersed from the mother plant. The seed bank serves as a repository, where these seeds get collected and ensure future populations, for annual and perennial weeds that reproduce exclusively by seeds.

However, those seeds that remain dormant or viable in the seed bank are extremely difficult to manage as they are buried and environmental factors such as soil temperature and soil moisture and exposure to light during land disturbance play vital in regulating their emergence pattern (Schonbeck and Egley 1980).

Climate related disasters such as flood or drought could influence, addition of weed seeds to seed bank as higher seed bank additions in fallow fields of Canada are attributed to absence of a competitive crop (Archibold and Hume 1983).

Only fewer of the seeds that enter the seed bank are successful in serving as a source of reinfestation. Most of them may die, decompose or predated upon. Mortality of wild oat (*Avena fatua*) seed increased up to 88% with increasing soil moisture over a period of two years (Mickleson and Grey 2006)

Once weed seeds enter the seed bank, they sense and interact with several factors in the surrounding environment. As a result either they become dormant or get triggered for germination (Gulden and Shirtliffe 2009).

### Ground Cover by Canopy or Smothering Potential

Smothering of co-inhabitants by canopy cover is also observed to contribute for invasiveness of *E. crassipes* (Kannan and Kathiresan 1998) and *M. quadrifolia* (Kathiresan 2002). One of the hypotheses that is attributed to invasiveness among wetland species is advantageous architecture that smothers other competitors (Zedler and Kercher 2004). Bisikwa *et al*. (2005) observed that differential growth response to light (shade avoidance) is not a mechanism of wild proso millet (*Panicum miliaceum* L.) displacing established stands of giant fox tail (*Setaria faberii* Herrm) in the field.

## 4. CASE STUDIES FOR SPECIFIC WEEDS FAVOURED BY A COMBINATION OF CLIMATE CHANGE EVENTS

### *Eichhornia crassipes*

The aquatic weed water hyacinth is ranked among the top ten weeds world wide (Holms *et al*. 1977) and is one of the most successful colonisers in the plant Kingdom. A native of Brazil, the weed spread to other parts of the world, through initial intentional introductions for its aesthetic values.

Rapid growth, vegetative reproduction and ability to reinfest via the seed bank or flood borne plants have resulted in excessive infestations in Africa, southern Asia and the USA. The weed impairs water quality and quantity, traffic, irrigation, hydro-electricity generation, water use and bio-diversity.

In Tamilnadu, a component state of India, Lake Veeranum, a storage reservoir that serves a command area of 18,000 ha of rice spread through the Cauvery river delta, has 27 distributary channels.

Survey in the distributary channels of lake Veeranum during 1990 and 2010 as furnished in (Table 3.) indicate that the invasive alien species of *E.crassipes* has invaded the watersheds in north Tamilnadu (Figure 3).

**Figure 3. *E. Crassipes* invasion in a watershed in Cuddalore district of Tamilnadu, India**

The meteorological data presented in Table 1. indicate that the average rainfall in the three segments of 1980-91, 1990-2000, 2000-2010 has been on the increasing trend along with the number of wet years (with annual rainfall in excess of 10 per cent over the average of previous 10 year segment). This indicates that the flash floods during the North East Monsoon has been more frequent, during the last 20 year segment.

The distributaries from lake Veeranum during the period before 1990 were mainly distributing the water from the river Cauvery, received from adjoining state of Karnataka. Accordingly, the water was flowing with higher velocity during the periods commencing from June extending up to December. However, after 1990, with dispute between the two states of Karnataka and Tamilnadu, these channels were mainly serving the purpose of draining outlets for flash floods during the North East Monsoon that were frequent during this last 20 year segment, besides distributing the comparatively lesser quantity of river water received during August and September. The flood waters from inland wetlands have served as infestation source of invasive species *E. crassipes*. (Kathiresan 2011), that has ultimately resulted in invasion of watersheds of North Tamilnadu by *E. crassipes*.

**Table 3. Survey of Aquatic weeds in five of the distributary channels of Lake Veeranum in Tamilnadu (IVI %) (Kathiresan 2011)**

| Weed species | Channel I | | Channel II | | Channel III | | Channel IV | | Channel V | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1990 | 2010 | 1990 | 2010 | 1990 | 2010 | 1990 | 2010 | 1990 | 2010 |
| *Ipomea reptans Per* | 10.3 | 6.4 | 21.3 | 4.8 | 14.6 | 3.1 | 19.6 | 6.0 | 27.2 | 2.9 |
| *Typha angustata L* | 1.3 | 3.2 | - | - | 2.7 | - | 7.2 | 2.0 | - | - |
| *L. chinensis* | 24.30 | - | 31.0 | 4.2 | 19.8 | 4.9 | 12.6 | - | 7.4 | 1.7 |
| *E. crassipes* | - | 39.42 | - | 46.4 | - | 42.6 | 7.8 | 58.6 | - | 63.4 |

***Parthenium hysterophorus***

*Parthenium hysterophorus* (ragweed *Parthenium*) is an invasive weed of tropical and subtropical environments. *Parthenium* species is native to Gulf of Mexico and Central South America, and has become widespread in North America, South America, the Caribbean and many parts of Africa, Asia and Australia. *Parthenium* is primarily found in wastelands, vacant areas, community parks, roadsides and even invades agricultural fields. It threatens human and animal health by dermatitis, hay fever, and respiratory problems in sensitive humans and animals. This species may have ecological implications on species diversity in various habitats.

The area under rice cultivation in South India is facing a slow decline due to several factors such as inadequate water supply low margin, increased labour cost and increasing urbanization and industrialisation. *Parthenium*, has been observed frequently on the road sides, railway tracks, wastelands and surroundings. A study was taken up with the objective of tracing the invasive behaviour of the weed as induced by the open niches due to decline in rice area in Cuddalore district of Tamilnadu State during 2000 – 2001 (Kathiresan *et al*. 2005).

Infestation of the weed *Parthenium* was not observed in any of the sampling sites in cultivated lands during any time of the year, throughout the two year study period. This indicates that the weed has not expanded into the cultivated lands in its process of invasion. This could be because of the fact that cultivated lands in this rice growing tract are puddled (ploughed with standing water) during preparatory tillage and water is impounded in the fields during majority of the rice crop's duration that occupies a minimum of one fourth of the year. This soil environment with excess moisture could have proved lethal for the seeds of *Parthenium*, thereby interrupting the process of invasion. However, in the wastelands, *Parthenium* was observed with considerable Importance Value Percentages ranging from 76 to 84 during the first half of the year or Spring commencing from February extending up to April (Table 4). With the onset of Summer from May, as the maximum temperature increased with dwindling soil moisture, the regeneration *of Parthenium* was not observed in these sampling sites on wastelands too. Cessation of hot summer in June and few showers of the first monsoon in July and August, recuperating the available soil moisture levels up to 42%, favoured sprouting of *Parthenium* and the second generation commenced with Important Value Percentages ranging up to 48. The second generation completed the life span before the heavy downpour of monsoon rains in the peak winter during mid November and another spell of interruption started during December and the same continued during January of next year. This could be due to heavy downpours (with more than 65 % of the annual rainfall of 1500 mm getting distributed during November and December months) over predominantly heavy clay soils in the coastal tract, resulting in frequent water stagnation.

**Table 4. Phyto-sociology *of Parthenium* in Veeranum ayacut region (Average values for 2000 & 2001) (Kathiresan *et al.* 2005)**

| Months | *Parthenium* Important Value Percentage | Available soil moisture (percentage) | Max. Temperature (°C) |
|---|---|---|---|
| January | - | - | 28.65 |
| February | 76 | 55 | 32.00 |
| March | 81 | 42 | 32.40 |
| April | 84 | 32 | 34.35 |
| May | 11 | 29 | 37.55 |
| June | - | 25 | 36.25 |
| July | - | 29 | 36.00 |
| August | - | 40 | 34.65 |
| September | 48 | 42 | 33.75 |
| October | 51 | 58 | 31.65 |
| November | 32 | 81 | 29.80 |
| December | - | 86 | 28.05 |

***Oryza punctata***

One of the main wild/weedy rice species in Africa south of Sahel is *O. punctata* which is an annual. The main weedy trait in this wild rice are seed shattering, dormancy and competitive aggression over cultivated species. Viability of the seeds declines more rapidly in excessive soil moisture. The periodicity in germinability and dormancy is observed to be influenced by seasonal climate changes favouring survival and propagation. Introduction of freezing temperatures induced dormancy and as the temperature increased, dormancy is released and germination process gets triggered (Delouche *et al*. 2007). Further higher moisture content combined with extreme temperatures are critical for induction of dormancy (Teekachunhatean and Delouche 1986). In the coastal region of Kenya, *O. Punctata* is a commonly occurring weed in rice fields. This weed has been observed to possess better biomass accumulation in both above and below ground plant parts, especially in the rice growing season (Munene *et al*. 2008).

***Prosopis juliflora***

Introduced from Central America as a drought tolerant species suitable for afforestation in arid and semi arid zones of India in 1877, *Prosopis juliflora* has invaded nearly 5.55 million hectares of land contributing for 1.8% of geographical area of the country. This weed has a wide geographic range over the tropics including Asia, Africa, South and Central America. Remote sensing data has predicted the expansion of the species in Gujarat State of India at the rate of 25km$^2$ per year. Reports predict that by the year 2020, more than 56 percent of the area in Banni with rich bio-diversity and grassland ecosystem would be under *Prosopis*. The most potential invasive feature of the species is typical greater assimilate partioning towards root, leading to extraordinary enlargement in the root mass with rich food reserves, aiding rapid and robust regeneration after mechanical lopping or after revival of ecological stress conditions such as drought or inundation. Studies at Annamalai University has shown that the root enlargement in *Prosopis* species is greatly influenced by the temperature regime of the locality. The annual increase in root bio-mass is greater in areas where the mean annual temperature is higher than that in areas of lesser mean annual temperature (Table 5).

**Table 5. Temperature regimes and root biomass enlargement in *Prosopis* (Kathiresan 2006a)**

| Mean Annual Temperature °C | Mean Annual Increase in Root biomass (kg) | Mean Annual Increase in Shoot biomass(kg) |
|---|---|---|
| 28 | 1.9 | 42 |
| 30 | 4.4 | 47 |
| 32 | 6.2 | 56 |

Increase in shoot biomass due to increasing temperature, though observed is not as significant as the increase in root biomass. The increase in root biomass (Figure 4) largely contributes for the weed’s ability to tolerate climatic extremes such as peak summer associated with high temperature and water scarcity and peak monsoon winter with water inundation and flooding. This adaptation favours the weed to predominate over other native flora that are susceptible to any one of the two extremes (Kathiresan 2006 a).

**Figure 4. Root biomass of *Prosopis***

Initially, the weed was observed to occur in areas of 150-750 mm mean annual rainfall. However, invasions have been recorded in large rice growing stretches of Cauvery River Delta in Tamilnadu state with mean annual rainfall of 1500 mm and where the occurrence of floods and inundation are common. In the southern dry districts of Tamilnadu, where Tank irrigation is the popular and only source of irrigation and village tanks that serve domestic water supply are also invaded. Large catchment reservoirs, wherein the rainwater during monsoon rains would be stored for use in subsequent drier seasons, have been invaded by *P. juliflora*. The species is able to withstand submergence in water for prolonged periods and come up protruding above the water surface with appreciable canopy and branches (Kathiresan 2006 a).

**Figure 5 Land mass infested by *Prosopis juliflora***

**Figure 6. Land mass after partial clearing**

Dispersal of the species is mainly through the animal aided seed dispersal by virtue of the process of endozoochory as the pods are succulent and are a preferred choice of food for animals. Further, use of stem as fuel wood by rural folk involves frequent lopping, upon which the root mass enlarges with rich food reserves, aiding rapid and robust regeneration. Invasion of pasture lands, protected forests, even water catchments reservoirs and arable lands by *P. juliflora* (Figure 5 & Figure 6) has alarmed agriculturalists and ecologists. Any disturbed, eroded, over grazed, drought affected land associated with unsustainable agronomic practice is vulnerable for invasion by the species. The species have many competitive ecological advantages like tolerance to a wide range of climatic and edaphic features, seed dormancy and animal aided seed dispersal. Such advantageous adaptations help the species to form impenetrable thickets. Though, the seeds are reported to be shade sensitive, the luxuriant growth of *Prosopis* bushes is observed in dense Tamarind (*Tamarindus indicus*) tree plantations of Salem district in Tamilnadu state. This proves the invasive potential of *Prosopis* as Tamarind itself is a strongly allelopathic tree species known for suppressing under storey vegetation with allelopathic principles and taller and larger crown. *P. juliflora* is considered as a weed over thousands of square kilometers in not only the arid and semi arid regions of India, but also in many other moderate climate and rainfall zones of India.

***Trianthema portulacastrum***

A major weed that has been invading irrigated upland agro eco-systems in several tropical Asian countries is *Trianthema portulacastrum*. This weed is reported to have originated from tropical Africa and has invaded several continents, *viz*., Australia, Africa and Asia (Rawson and Bath 1984; Yaduraju *et al*. 1980). A survey conducted in different irrigated upland crops of Veeranum Ayacut in Tamilnadu, India indicate that *T. portulacastrum* predominates as the dominant species in all the three crops *viz*., sugarcane, sunflower (Figure 7 & Figure 8) and gingelly with Important Value Index percentages of 28.73, 26.83 and 25.99, respectively. This weed tops the list of 15 weed species recorded in all these crops in different locations. (Kathiresan 2004). One of the most important characters responsible for its invasiveness is thermal induction of seed germination with soil temperature around 35°C favouring synchronized and mass germination of seeds, covering the soil as a green carpet. In a field study conducted at Annamalai University, it was observed that, increasing soil temperature with the summer months of June and July triggered the mass germination of seeds of this weed suppressing the native species (Table 6). The seeds of this weed undergo dormancy during winter and thermo-induction to break the dormancy requires soil temperatures above 35°C (Kathiresan 2006b).

**Table 6. Thermo induction of seed germination in *Trianthema portulacastrum* (Kathiresan 2006b)**

| Month | Seedling emergence 15 days after land preparation at the beginning of the month ($m^{-2}$) | Monthly average max. temperature (°C) |
|---|---|---|
| January | 8.5 | 28.5 |
| February | 11.6 | 30.4 |
| March | 16.7 | 33.1 |
| April | 23.4 | 34.2 |
| May | 32.9 | 36.9 |
| June | 85.6 | 37.3 |
| July | 102.4 | 36.2 |
| August | 126.8 | 35.0 |
| September | 20.5 | 33.9 |
| October | - | 31.2 |
| November | - | 28.7 |
| December | - | 28.1 |

**Figure 7. *T. portulacastrum* in early stage of sunflower crop**

**Figure 8. *T. portulacastrum* smothering sunflower crop**

***Solanum elaeagnifolium***

*Solanum elaegnifolium* commonly called as silver leaf nightshade has been introduced from North America to Africa, Asia, Australia, Europe and South America where it is an important weed of croplands and pastures, mostly in cultivated land, disturbed areas and overgrazed areas with low rainfall. The invasiveness is aggravated by high seed production and an extensive root system that promotes vegetative multiplication and renders conventional control methods very difficult. Other negative effects include hindering commercial cropping activities, harbouring agricultural pests, being toxic to livestock and reducing land values. The plant is officially declared as a noxious weed in several countries. The impact of temperature regimes on the phenology of the plant with flowering during summer resulted in reduced the flower visitation of native *Glaucium flavum* by pollinators and pollen limitation (Tscheulin *et al*. 2009).

This weed prefers high summer temperatures and lower annual rainfall (Heap *et al*. 1997). Lower temperatures and high rainfall are the limiting factors that restrict range expansion (Heap and Carter 1999). While the weed is drought and saline tolerant, it is highly sensitive to water logging and frost. Accordingly increasing temperatures, alternating periods of soil moisture deficit and surplus periods that are forced in the semi-arid tropics by climate change could prove to be a inducing factor for invasive behaviour of *S. elaeagnifolium.*

***Commelina benghalensis***

*Commelina benghalensis* also known as tropical spider wort originated in tropical Asia and Africa. The weed is introduced in to USA recently, specifically in south eastern USA, *viz*. Alabama, Florida, Georgia and North Carolina. Growth responses of this weed are assessed under ambient and elevated $CO_2$, in USDA-ARS, Auburn, Alabama. Elevated $CO_2$ increased the leaf and flower number by 23% while leaving the plant height unaffected. Leaf flower, stem and total shoot dry weights are increased by 36, 30, 48 and 44%, respectively. Root dry weight and root length are left unaffected. Carbon content is also increased by elevated $CO_2$ where as plant nitrogen is observed to be lowered, thus leaving the plants under elevated $CO_2$ to be with higher C/N ratio (Price *et al*. 2009).

***Cassytha filiformis***

The species of *Cassytha* are generally distributed in Australia, Africa, America and Japan (Mabberley 1997). It occurs as a stem parasite on lantana and certain other plants in south India (Rangasamy and Rangan 1963). Several host plants *viz*., *Bougainvillea spectabilis*, *Citrus aurantifolia*, *Nerium oleander* and *Morus alba* L are reported to be infested in Pakistan (Mukhtar *et al.* 2010).

The plant *Cassytha filliformis* is a twining parasitic, perennial that adheres to the host by haustoria. The seed germination is induced by lower winter temperatures and the general phenology prefers warm tropical temperatures coupled with higher humidity levels. However the potential negative effects are shown to be stronger on introduced host *Cytisus scoparius* than a co-variant native host *Leptospermum myrsinoides* indicating the possibility of *Cassytha* for use as a bio-control tool (Prider *et al*. 2008).

***Cuscuta campestris***

*Cuscuta campestris* called as dodder is a parasitic weed of the Convolvulaceae family, widely occurring in temperate and subtropical ecosystems. The weed posses dormancy and the temperature optimal for seed germination is observed as 30ºC (Benvenuti *et al.* 2004). Blue light stimulates and Red light inhibits prehaustoria development (Hutchinson and Ashton 1979; Haider *et al.* 2004). Parker and Riches (1993) attributed the germination of dodder early during spring season to the loss of dormancy during cold winter months.

***Rhamphicarpa fistulosa***

This weed belongs to the family Orabancheceae widely prevalent in West Africa, Madagascar and South Africa and is an important parasitic weed in rice. It is restricted to unimproved lowlands including inland valleys. It is an annual facultative root parasite, mainly parasitizing tropical cereals, through a haustorium connected to the host roots (Neumann *et al*. 1998). Significant yield reductions in rice, due to *R. fistulosa* is reported by Gbehounou and Assigbe (2003). *R. fistulosa* is well adapted to flash floods and partially flooded conditions of wetland transplanted rice. Heavy precipitation and higher temperatures predicted for sub-saharan Africa (IPPC 2007) could have stimulated invasive expansion of *R. fistulosa* in these countries. Survey in rainfed lowland rice in Benin as reported by Rodenburg *et al.* (2009) shows steady increase of *R. fistulosa.*

***Striga hermonthica***

*Striga hermonthica* commonly known as witch weed of the family Orabanchaceae is capable of parasitizing sorghum, maize pearl millet, rice and sugarcane. Native to Africa, *S. hermonthica* is a serious pest to cereal production, causing 70 to 100 per cent crop loss in maize, sorghum and pearlmillet in Nigeria (Emechebe *et al*. 2004). Ecological niche models using GARP predicts wet areas receiving 50-150 cm of annual rainfall coupled with annual mean temperature ranges of 20-30ºC to positively interact with *S. hermonthica* resulting in favoured range extension in tropical, sub tropical and semi and regions comprising Africa, Arabian Peninsula, South Asia, South East Asia and Australia (Mohamed *et al*. 2006). Seed dormancy that persists for six months require sufficiently warm and humid conditions for about one to two weeks as a pre condition besides xenognosins from host, to enter in to germinable state (Vallance 1950; Yoder 2001).

**Sleeper Weeds**

Sleeper weeds are those invasive plants that have naturalised in a region but not yet increased their population size exponentially (Groves 1999). Those weeds that have entered a new range and established but currently undergoing a lag phase before going through the phases of expansion, explosion and entrenchment in the process of biological invasion are considered under this category. However, they deserve better attention and watch in order to reduce the impact of these green invaders. A study of Bureau of Rural Sciences, Australia identified 117 possible sleeper weeds in the continent. Later the list is narrowed to 17 as to have been causing nationally significant impacts on agriculture if allowed to spread. Subsequently BRS study identified Uruguayan rice grass *Piptochaetium montevidense* (Spreng.) porodi as a sleeper weed that is economically worth an eradication programme. The sub alpine and alpine sleeper weed, orange hawkweed (*Hieracium aurantiacum* L.) has also been identified but not deserving eradication inspite of being retained on appropriate weed lists, during 2006. A review of these two weeds during 2009 reveals that Uruguayan rice grass has been eradicated but orange hawk weed continues to expand (Baker 2010). This indicates that the eradication of some naturalised plants before their expansion as problematic weeds is a more economically feasible option.

## 5. RECOMMENDATIONS FOR PREDICTION AND PREVENTION OF WEED INVASIONS INDUCED BY GLOBAL CLIMATE CHANGE

Several thousands of the alien species have become established in different parts of the world over the past couple of centuries. One in seven has become invasive. The success of an introduced weed in getting established and behaving invasive often depends on climatic parameters that they interact with. Accordingly the impact of climate change on invasive traits of weeds could ultimately be reflected on varied dimensions of resource and biodiversity conservation as well as agricultural production.

Prediction and prevention of weed invasions induced by climate change assumes significance as such impacts listed below are imminent.

1. Extension and change of geographic ranges of introduced weeds
2. Established populations of weeds that might have become extinct otherwise
3. Herbivory, predation, disease, parasitism, competition, habitat destruction, hybridisation and changed disturbance regimes (Simberloff 2000).

Precise predictions and proper prevention of such invasions require intense research to fill up the knowledge gaps and generation of a global database or repository of informations on invasive traits of weeds influenced by climatic parameters.

**Research Needs**

1. Scientist with expertise on matching climate parameters with invasive traits of weeds should publicise knowledge base with informations that have already been well understood and uncertainities that need to be explored.
2. Funding for these studies need to be encouraged under the aegis of climate change related agencies, organisations and frameworks.
3. Policy makers need to make science based decisions, incorporating the knowledge base in the policies (*viz.* listing quarantine pests, exercising control on sleeper weeds etc.)
4. Policy makers should include invasive weeds in any national, regional or global assessment of climate change on agriculture.
5. Research is required for quantification of impact of invasive weeds on agricultural productivity, native biodiversity and resource base.
6. Research should also be involving advanced techniques especially in terms of hyper spectral remote sensing and bioclimatic modelling programs.

**Knowledge Sharing and Database**

It is essential that every country develops weed database including of noxious weeds in different ecosystems. Such information will help each country to prepare its own list of weeds which they consider are potential invaders. Many developing and underdeveloped countries require assistance from international agencies in development of such databases and in weed risk analysis exercise. Directory of people and organizations involved in the study and control of particular weed species would be of help in early detection and subsequent management of invasive weeds. The literature and database on distribution, ecology and biology of introduced species are also scarce. FAO of United Nations could take up a lead role in organising such a network.

**Weed Risk Assessment**

Once a weed species is predicted to be invasive and listed as a prohibited species under quarantine regulations, impact of invasions could be drastically reduced. Different prediction models have been studied and proposed (Panetta 1993; Pheloung 1995; Reichard and Hamilton 1997; Maillet and Lopez Garcia 2000; USDA 2000; Champion and Clayton 2000; FAO 2005). The latest WRA outlined by FAO in 2005 has a set of questions towards scoring for weed risk factors. **However, none of them pertain to response of the species to climate.**

Weed species that are favoured under a specific combination of the climatic parameters that could result in due course may be predicted based on climate resilient weed risk scores. Climate resilient weed risk scores are computed on a relative basis for individual weed species, through a system or matrix, that comprise the above listed impacts on invasive traits by the changing climate, in a logical sequence. However, instead of adding up the values for each of the weed trait versus variable climate (II) it is suggested that products are formed between them in order to eliminate those species that would suffer for survival, due to changing climate, from the watch list.

**Awareness Creation**

Each country must develop a fact book to raise awareness of public, farmers, developmental agencies, legislators, fellow researchers, students, tourists and others about invasive plants. It should contain basic information about weeds in different ecosystems. It should highlight the dangers of invasive weeds, their identification, and their management. Organising events such as ‘weed awareness week’ (in USA) ‘weed buster week’ (in Australia) are worthy approaches. A new National Early Warning and Rapid Response System for Invasive Plants is being developed for practice in USA (Westbrooks *et al*. 2001). Developing similar programs would benefit all member nations of UN.

**Guidance and Advice to Policy Makers**

Research on impact of climatic parameters, climate change and natural disasters on invasive behaviour and traits of weeds need to be encouraged with substantial funding under the aegis of climate change related agencies, organisations and frameworks.

Policy making need to make science based decisions, incorporating the knowledge generated in those policies, such as listing of quarantine pests, exercising control on sleeper weeds, etc.

All national, regional or global assessment of impact of climate change on agriculture, biodiversity and environment should encompass the impact on invasive weeds.

Developing national database on noxious weeds, invasive alien weeds and weed risk assessment in different ecosystems need to be insisted for all member countries. Underdeveloped nations should be considered for assistance from international agencies in development of such databases.

FAO could organise a network comprising experts and organisations involved in the study and control of invasive weeds.

An uniform weed risk analysis procedure that includes climate resilience scores should be developed by FAO and disseminated for adoption by all the member nations.

FAO could encourage organising events for raising awareness about invasive weeds, among public, in member nations.

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