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Desert Locust *Schistocerca gregaria* Forskål (Acrididae): Biology, Management and Strategies: A Review

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ABSTRACT

Early 2020 witnessed the emergence of global agrarian crisis with the widespread burgeoning of the destructive migratory pest, Desert Locust (*Schistocerca gregaria*) in East Africa, South-west Asia, Pakistan and India. Characterized by the ability to eat ravenously, breed exponentially and migrate rapidly; locust swarms has led to substantial agrarian disaster. The current official strategy is to control the upsurges to evade plague. Though the strategy may seem attractive and efficient, it is sensible only if the numbers are relatively low. The socio-economic and environmental challenges posed by the unprecedented locust outbreak has prompted the scientists worldwide to emanate an effective preventive management strategy based on updated knowledge of pest biology, ecology and behaviour along with efficient monitoring, data management, analysis, forecasting, resource deployment and control techniques. Additionally, the integrated network of field teams, decision makers, analysts, rural governing bodies and farmers could potentially offer better compliance to the pest management strategies.

Key words: Gregarious, Hopper band, Outbreak, Plague, Solitary, Swarm, Upsurge.

Locusts are the grasshoppers exposed to specific environmental cues that develop into phenotypic variants like gregarious, swarming or solitarious (Cullen *et al*., 2017). The morphology, physiology and behaviour of these phenotypes are found to differ categorically. Although, the plasticity of traits (polyphenism) such as morphology and physiology may take several generations to shift, but the behaviour may show shift within a few hours in some species (Pener 1991; Pener and Simpson 2009). At low densities, locusts play a critical role in nutrient cycling, plant community structuring and food chain (Sokol-Hessner and Schmitz 2002; Schmitz 2008; Branson *et al*., 2006). Further, they are the important food source for animals like spiders, birds and even humans too (Stoops *et al*., 2016; Osimani *et al*. 2017), as they are the second highest consumed insect after crickets. However, they pose challenge by competing for food with other insects and livestock at high densities. Cigliano *et al*. (2017) stated the 6,800 acridid grasshopper species as locusts. As per the Food and Agriculture Organization (FAO), the phase changing desert locust (*Schistocerca gregaria* Forskål) is considered as the most important locust species because of its astounding migratory, feeding and reproductive capabilities. A single swarm can cover up to 1200 sq. km (Shaluf 2007). The swarm of a sq. km can potentially eat the same amount of food sufficient to feed about 35000 humans in a day. Further, the population of the locust rises exponentially to a catastrophic level within a few generations of breeding; 20 time increase in 3 months, 400 times in 6 months and 8,000 times in 9 months (FAO 2020a). Apart from the damages caused to pastures, the subsequent loss of vegetation cover due to the infestation of locusts leads to soil erosion. Although, a better monitoring of the locust has been made possible with the advancement of human understanding of pest biology and use of high-end technologies like the satellite imagery and geographic information systems, still the world has been struggling with the locust upsurge, which has the potential to amplify into a plague. Therefore, here we outlined the chronology of current locust upsurge, pest status, feeding habits, life cycle, ecology, behaviour, management strategies, challenges while managing the pest swarms and potential areas of further research and policy making.

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Recent locust upsurges

Recently, the world has witnessed even greater risks of locust swarm upsurge in the context of unprecedented weather events associated with the climate change. During recessions, the desert locusts were found restricted to semi-arid and arid deserts of Africa and Southwest Asia as these regions receives < 200 mm of rainfall annually. The upsurge during 2020 began with the breeding of locusts for three generations (increase in locust population up to 8 fold) in over nine months as a result of two cyclones (May and October 2018) that brought heavy rainfall to empty quarter in the Arabian Peninsula. Swarms started migrating from these areas to the Arabian interior (invading southwest of

Islamic Republic of Iran) and southward (invading eastern Yemen, eventually bred because of the weather conditions after widespread heavy rains and remained unnoticed for at least one generation).The southwest of Iran which had not seen swarms in last 50 years, had witnessed unusual heavy rains and floods in 2019. Thereafter, the swarms spread to the southern coasts of Iraq, Baluchistan and Pakistan with two generations of breeding. From there, the spring-bred swarms started migrating to the east and invaded the desert area along the Indo-Pakistan border. Despite of the massive control operations, the locust swarms became unstoppable as they were favoured by heavy annual monsoon rains (in 2019 monsoon lasted one month longer than normal), which allowed them to breed for 3 generations (from May 2019 to January 2020). While, some summer-bred swarms migrated to Iran (in late 2019); other swarms remained in Pakistan (in early 2020). The locust generation unnoticed in Yemen had now invaded the eastern Ethiopia and northern Somalia. The control measures were failed because of the massive rainfall in Ethiopia. The decline in locust population was expected at that time because the Horn of Africa dries out by the end of most years. But this time it was contradicted by unexpected cyclone Pawan in early December 2019, which resulted in heavy rains both in eastern Ethiopia and Somalia. This eventually led to the favorable breeding conditions up to June 2020. Thus, the formation of hopper bands in March 2020 took place and new generations of swarms were observed during April 2020 in Ethiopia and Somalia. Later, the swarms get matured and laid eggs continuously to form hopper bands (FAO 2020b - Desert Locust Upsurge, Global Response Plan). Populations moved from spring breeding areas of Pakistan and southeast Iran towards the end of May 2020.

Swarm update in south west asian countries

In Iran and Pakistan, the spring breeding has come to an end and swarms were expected to move to the Indo Pakistan border. In India, the locusts entered through the Indo-Pakistan border to Badmer, Jodhpur and Ajmer districts of Rajasthan. Thereafter, they were reported in Ujjain, Sihar and Mansor of Madhya Pradesh. Eventually, the locust swarms were spotted in Jaipur (Rajasthan) and Jhansi (Uttar Pradesh). The change in rainfall patterns may be attributed to positive Indian Ocean dipole resulting in high temperature in the western Indian Ocean. This resulted in record-breaking rainfall in India. The bizarre mild summer with several incidences of rainfall over the north-west India from March to May helped in breeding of insects, which created the situation may worsen. As per Locust Warning Organization, swarms have covered the areas of Rajasthan, Gujarat, Madhya Pradesh and Uttar Pradesh. Also, in India, breeding has occurred in areas of Bikaner from where hoppers were emerged during the third week of June, while a total of 33,867 ha have been covered under control operations.

Desert locust: feeding habits, pest status, habitat and ecology

Feeding habits

Schistocerca gregaria is a polyphagous locust species that eats many families of plants, and considered as a potential threat to livestock forage and an array of crops. A wide range of food preference allows them to withstand and migrate through many agro-ecosystems. This species mainly prefers overgrazed and disturbed habitat because it supports an exposed bare soil, which is optimum for their egg laying and thermoregulation. In agricultural areas, desert locust prefers cultivated areas in contrast to the trees and shrubs in grazing areas (Wilps and Diop 1997; Van *et al*. 2005). A study carried out by Van *et al*. (2008) stamps on a positive correlation between survival rates and nitrogen based diets. The abundance of *S. gregaria* was also found higher in areas with low grazing pressure and higher nitrogenous plants.

Habitat and ecology

Desert locusts are well-adapted to live in vast and arid landscapes. During the recession years, they are found living in arid and semi-arid zones of the western coast of Africa to north-west India receiving an average annual rainfall of approximately 0-400 mm. Also, a sporadic and unpredictable rainfall with about 70% above or below average makes the locusts outbreaks unpredictable (Cressman 2016). Since, *S. gregaria* is multi-voltine; they can breed up to three generations under favourable conditions. Also, the locusts have remarkable migrating capabilities up to 150 km in a day. Interestingly, they typically migrate between seasonal breeding areas (Pedgley 1981) in a way that their population

Behavioural modifications

The reduction in resources, resource distribution and change in food quality are the factors that increases the chances of locusts' gregarisation (Despland and Simpson 2000; Cisse *et al*. 2015). This behavioural shift occurs within a few hours and may be attributed to the secretion of serotonin which induces sudden behavioural changes like increase in activity and attraction to conspecifics (Anstey *et al*., 2009; Rogers *et al*., 2014). Many studies back the process of behavioural shift as anti-predator strategy. The development of aposematic colouration and acceptance towards food with alkaloid hyoscyamine (which gives them gut content-mediated toxicity) also insists on the behavioural shift to escape predators (Despland and Simpson 2005; Sword 2001).

Life cycle of the desert locust

The lifespan of desert locust ranges from three to five months, depending on various environmental factors. Usually, the life cycle comprises three different stages *viz*. egg, hopper and the adult (Fig 1). The female usually probes the soil about 5-10 cm deep before lying eggs by inserting the abdomen tip to assess the moisture level. The batches of eggs (70-80 eggs in gregarious phase and 90-160 eggs in solitary phase) appear like rice grains clustered together and are referred as egg pods. Typically, the swarms lay egg pods in dense groups with foam that helps in inducing gregarisation later. A single female can lay egg at least three times in their lifetime with an interval of 6-11 days. The development of the egg was found seized below 15°C temperature. The incubation period ranges from 10–12 days at optimum temperature of 32-35°C. Eggs hatch into hoppers in 2 weeks; hoppers undergo five and six instar stages in gregarious and solitarious phase over a period of 1-1.5 month, respectively. The rate of development of instar stages depends upon the temperature. Increase in daily air temperature from 24- 32°C leads to a decrease in hopper development period. At 37°C, instar development takes 22 days, while the process may be delayed up to 70 days at lower temperatures. Meanwhile, the hoppers continue to concentrate and become more gregarious. Such type of fusion of groups is referred as hopper bands. When the vegetation dries out, the adults will fly downwind to distant places in search of food and favourable breeding conditions. The solitary adults fly at night for few hours. In contrary, the gregarious adults fly during day light. Hopper bands follow alternate roosting and marching behaviour during warm days. However, bands can move only to small distances. For example, bands with predominantly fourth instar can march about 200 m to 1,700 in a day. Finally, the fifth instar nymph moulds into the adult stage. Thereafter, fledging occurs and the adults acquire wings which strengthen after a few days. A swarm of adults fly several kilometers downwind from laying area and spend the night roosting in vegetation.

Phase transition

During recession periods, when unusual rains feed the breeding areas, locusts multiply rapidly and increase their number. Once the desert habitat starts drying out, the locust population is forced to remain in proximity of the whatsoever little patches of vegetation present. This leads hoppers to contact more frequently and start behaving like single cohesive mass. As, they become more gregarious, initially as small hoppers groups (wingless nymph) and later as adults, they eventually fuse to form dense bands of hoppers and swarms of adults, respectively. Also, downward wind tends to bring locusts into areas expecting rainfall. The rainfall fed areas allow locusts to mature and breed. This entire series of behavioural modification is called as

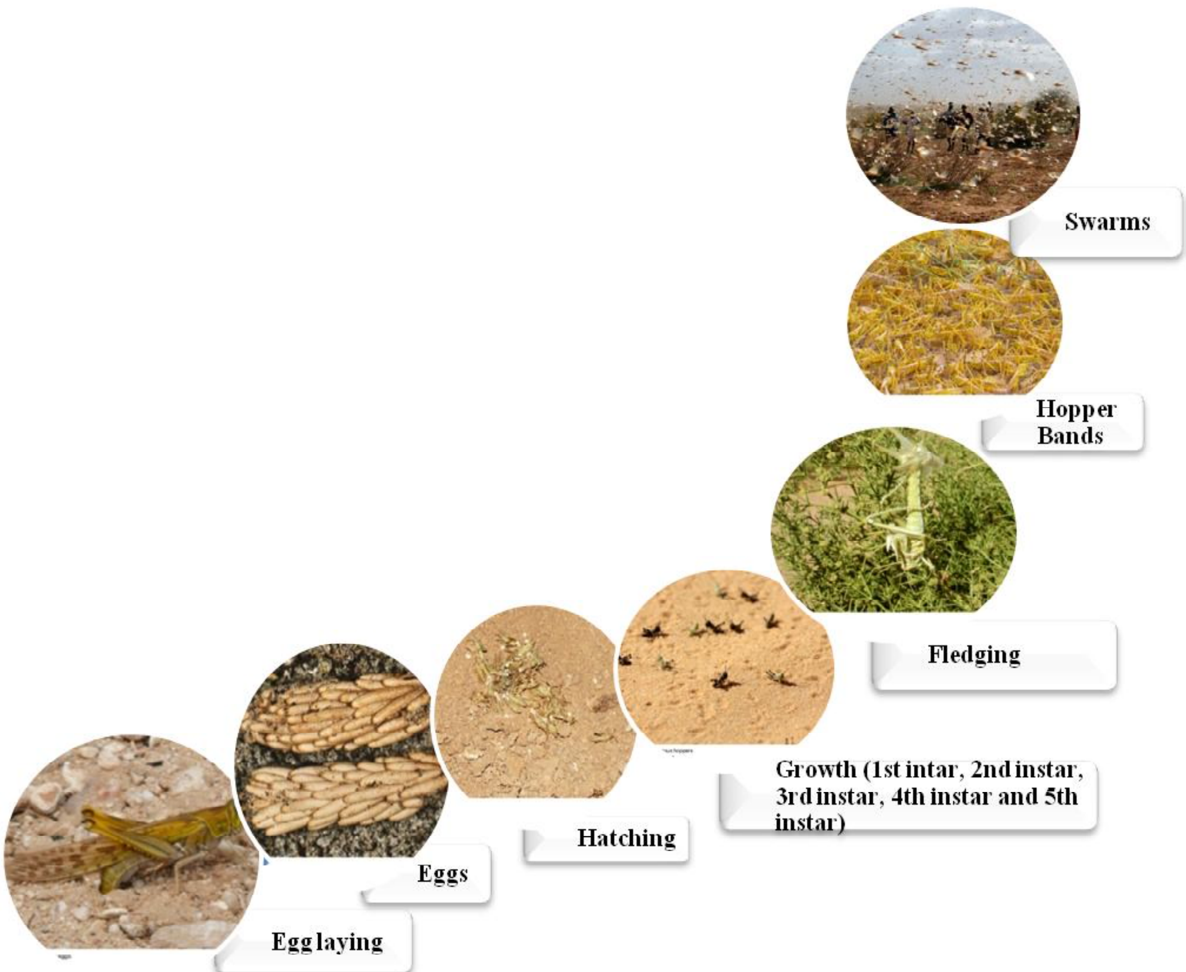

Fig 1: Schematic representation of the life events of desert locust. (Photograph source: FAOLocust/desert-locust-photos).

Table 1: Differences between solitarious and gregarious phase of locusts.

Phases	Behaviour	Colour	Morphometrics
Solitary	• Roost, bask, feed and move as individuals • Move short distances and adults generally fly at night.	• Hoppers green in early instars and brown in last two instars. • Adults are pale h brown. • Males change color to pale yellow upon sexual maturation. Female don't exhibit color change in low densities.	F/C Male 3.75 and above Female 3.85 and above E/F Male 2.025 or below Female 2.075 or below
Gregarious	• Roost, bask and move in groups. • Fast moving and fly as swarms in day time.· • Hoppers move in band.	• Hoppers are yellow in color with black patches.· • Adults darken with age from rosy pink to yellow on sexual maturation. • Males are brighter.	F/C Male 3.15 or below Female same as above E/F Male 2.225 and above Female 2.272 and above

C = Width of head, E = Length of forewing, F = Length of hind femur, measuring Unit in millimeter.

gregarisation and the intermediary phase between solitary and gregarious adults is referred to as transiens. The differences between solitary phase and gregarious phase have been mentioned in Table 1. As per Symmons and Cressman (2001), gregarisation can occur only in the areas where two generations of breeding can occur in rapid succession.

Breeding seasons

Breeding seasons of desert locust may be categorized in three phases (a) Winter breeding which occurs from November to December in coastal plains bordering the Red Sea and the Gulf of Aden, coast of South East Arabia and the Mekran coast of Iran and Pakistan (b) Spring breeding that extends from January to June in areas of the western Sahara, Mauritiana, south and central Algeria, Libya, Chad, Red Sea, the gulf of Aden coastal plain, South Arabia coastal plains, central Arabia coastal plains, eastern Arabian coastal plains and Afghanistan. (c) Summer breeding that occurs from July to October in southern fringes of Sahara that includes areas from Mauritiana to Sudan, coastal areas of Ethiopia and Southern Arabia, Mekran, Tharparker and Cholistan desert of Pakistan and the desert areas of Rajasthan, Gujarat and Haryana (North west India).

Pest status

Desert locust as the name suggests, originated in the desert regions of North Africa, Middle East and Southwest Asia and was infamously known because of its extensive expansive invasion zone across the world. Desert locusts have drawn the attention in biology research for its extensive life history (Symmons and Cressman 2001; Pener and Simpson 2009; Cullen *et al*., 2017), food choices and nutrient balancing (Maxwell-Darling 1936; Chandra and Williams 1983; Behmer *et al*., 2001). The devastation caused by *S. gregaria* was recorded the earliest in 2420 BC in Egyptian tombs (Nevo 1996). Before 1963, plagues generally persisted for 7-14 years (Symmons and Cressman, 2001). The desert locust invasion in Morocco (1954-1955) caused losses of over 50 million USD just in six weeks in Souss-Massa Valley alone. In 1958, desert locust led to the loss of 167000 tons of grain in Ethiopia, which was sufficient to feed one million people for one year. Altogether four plagues were occurred in between 1965-2006 and lasted for less than three years (Magor *et al*., 2008). However, plagues persisted for shorter time periods. This decline in plague duration may be attributed to the implementation of preventive measures for desert locust control (Symmons, 2009). During desert locust plague (2003-2005) that affected Africa, 13 million ha of land was treated. It took more than 500 million USD, 13 million liters of pesticides and two years to control desert locust plague in the northern parts of Africa. Despite of this massive amount of input, plague spread to the Middle East and resulted in 100% cereal crop losses (Cressman 2016). From 2005 to February 2019, no globally affecting plagues were reported. Recently (2019 and 2020), starting from the Horn of Africa, swarms have invaded Iran, Iraq, Pakistan and India. Since, the desert locusts eat a wide variety of crops and other plants including vegetable, fruits and cereal crops, experts have warned of extreme crop losses if not controlled appropriately. Past incidences of upsurges and plague in India are detailed in Table 2.

Understanding the phases of desert locust invasion

Recessions are the periods in which species reverts to transiens, solitary phase and swarming populations almost decline. Locally, locust outbreak can be marked by initial increase in locust numbers due to continuous multiplication, concentration and gregarisation; which eventually leads to the formation of hopper bands and swarms (Roffey and Popov 1968). This entire series of population growth is called as outbreak. When supported by intermittent rainfall, locusts breed for two or more successive generations of transient to gregarious breeding occupying expanded areas, which is known as upsurge. If the widespread of locusts continue for one of more consecutive years with heavy infestations in forms of bands or swarms, it is referred to as plague. Invasion area of the locusts during upsurges and plagues has a potential of covering 20% of the earth's land surface which is approximately equivalent to 32 million square kilometers which covers many countries (Cressman 2016). The outbreaks cannot be controlled mainly because they develop abruptly in remote areas particularly. Insufficient preparedness and lack of resources at that particular time and country adds to the outbreak (Roffey and Magor 2001). However, it is also interesting to see that the plague declines within six months, which is way quicker than the time it takes to develop. Often, it takes more than 3 years for a plague to develop, but it declines within six months after it has achieved its peak.

Transboundary coordination for monitoring locust outbreak

The cross border spread of locusts in epidemic proportions has led to the integrated collaborations of international and national bodies. Their management and control requires well knitted system of regional and international coordination and cooperation. Internationally, the Locusts and Trans-boundary Plant Pests and Diseases Group at FAO of United Nations headquarters are responsible for aiding the countries in managing desert locust outbreak. FAO closely monitors the global locust crisis and aids in forecasting, early warning and timely alerts the nations about timing, scale and locations of locusts' insurgence and breeding using its global Desert Locust Information Service (DLIS). The nations affected by locust outbreak transmit the local data to FAO, which in-turn analyze the brought data in to with weather, wind direction, habitat and satellite data. Thereafter, it provides the nations with forecasts up to six weeks in advance and issues advisory in monthly bulletins and periodic updates. Also, FAO focuses on strengthening the national capacity, substantial field assessments, surveys, control operations and emergency assistance during locust upsurges.

Table 2: Previous control campaigns carried out in India.

Year	Status	Time period	Type of campaign	Areas treated	Total area treated (ha)	Pesticides used (kg/l)	Pesticide used
1993	Upsurge	July-October	Yellow/Pink desert locust hoppers and swarms (190 Nos)	Jaisalmer, Barmer, Jalore and Bhuj	310482	688255 30934 47577 36860	BHC 10 % Dust Dieldrin 18% Malathion ULV Fenitrothion ULV
1997	Upsurge	July-October	Yellow/Pink desert locust hoppers and swarms (04 Nos)	Jaisalmer and Barmer	23596	7974 3660	Fenitrothion ULV Malathion ULV
2002	Outbreak	July, 2002	Migratory locust population	Jodhpur	42	42	Malathion 96% ULV
2005	Outbreak	September to December, 2005	Loose pink swarm and hoppers	Jodhpur, Bikaner, Jaisalmer	16,640	10,476 1883	Malathion 96% ULV Fenitrothion 96% ULV
2007	Outbreak	April to September, 2007	Loose pink/ yellow swarm and hoppers	Jodhpur, Bikaner, Jaisalmer	236	536	Malathion 96% ULV
2010	Outbreak	October to November, 2010	Hoppers/ fledgling	Jaisalmer	4,700	4,700	Malathion 96% ULV
2016	Outbreak	June, 2016	Migratory Locust, etc.	Leh area of J&K	1205	1928	Chloropyriphos 20% EC
2016	Outbreak	November, 2016	Tree locust	Jodhpur	40	40s	Malathion 96% ULV
2017	Outbreak	November, 2017	Tree locust	Jodhpur	40	40	Malathion 96% ULV

(Source: http://ppqs.gov.in/divisions/locust-control-research/locust-plagues-and-upsurges).

Since, locust belt is widespread across many countries, International Conferences have divided the Desert Locust Belt into following five regions: (a) South-West Asia Region- India, Pakistan, Iran and Afghanistan (b) Near East Region- Iraq, Kuwait, Jordan, Lebanon, Saudi Arabia, Turkey, Syria, United Arab Republic, Egypt, Bahrain, Yemen Arab Republic and the People's Republic of Southern Yemen (c) East African Region- Ethiopia, Djibouti, Sudan, Kenya, Tanzania, Uganda and Somali Republic (d) North-western African Region- Algeria, Libya, Morocco and Tunisia (e) West African Region- Chad, Dahomey, Cameroun, Ivory coast, Gambia, Mali, Mauritiana, Niger, Senegal and Upper Volta. Desert Locust Control Organization for East Africa (DLCO-EA) is operational regional locust organization in Africa that specializes in aerial surveillance and control of desert locust, grain eating birds and tse-tse fly.

Controlling the Desert Locust in South-West Asia (SWAC) is an FAO commission established in the year 1964 for locust prevention, strengthening national capacities and conducting field surveys consists of four countries *viz*. Afghanistan, Iran, Pakistan and India. The commission is headed by Senior Locust Forecasting Officer at FAO. In India, Locust Warning Organization (LWO), a division of Directorate of Plant Protection, Quarantine and Storage (DPPQ, Faridabad) is responsible for early warning, timely guidance and advisories regarding locust upsurge. The LWO also assists in the control and management operations carried out across the locust invaded area to protect the standing crop and vegetation from the destructive migratory pest. The operational field headquarters of LWO is situated in Jodhpur which carries out all the technical activities in collaboration with 10 Locust Circle Offices (LCOs) located in the state of Rajasthan (Phalodi, Nagaur, Churu, Suratgarh, Bikaner, Jaisalmer, Barmer, Jalore) and Gujarat (Palanpur and Bhuj).

Strategies to manage the locust upsurge

Interestingly, locust takes at least a year or more for a plague to establish. Factors like successful control, rainfall failure, and migration to unfavourable areas can control upsurges from becoming plague. The size of a flying swarm (m) can be calculated by using wind speed with the formula: time (sec) × width (m) × wind speed (m/sec). However, this formula over-estimate the swarm size but then also, it can hint on the extent of upsurges and plagues. Thus responsible surveys, proper data assessment, early warnings and robust control operations can control locust upsurges successfully in initial phases. As per LWO, "There are no preventive measures to control locusts". Holistic approach while planning for the control measures, taking into consideration the pest biology and behaviour is pivotal for program efficiency.

Biological control

Recent scientific advancements have stamped the potential use of bio-pesticides in locust management (Love and Riwoe 2005). Sprayed over 100,000 ha/ year in China, both fungus *Metarhizium anisopliae* var. *acridum* and microsporidian *Paranosema locustae* have revolutionized the mechanism of locust control. These two biocontrol agents have remarkable mortality rates though at longer time as compared to that of chemicals. The fungus penetrates the cuticle of the locusts, grows inside its body and subsequently kills it. Commercial formulations, Green Muscle^{TM} and Green Guard^{TM} are being used in Australia on large scale for locust control. Furthermore, the natural enemies of locusts not targeted by these bio-pesticides are preserved. However, the use of such bio-pesticides is still limited to China, Mexico and few parts of East Africa. The potentials and limitations of these bio-pesticides are being evaluated under African climatic conditions by FAO. Though these options have relatively slow mode of action, yet they offer an excellent solution in ecologically sensitive areas or areas where the vegetation is less affected by locusts.

Cultural control

Cultural method of control like making loud noises has been adopted by the farmers at the local level to prevent the crop losses with limited localized impact. These noises do not let the swarms to settle on crop and eventually the crop is saved from locust attack.

Chemical control

Mostly, locust control programs depend on the chemical pesticides. However, the control strategy must be understood in different phases (a) Management of locust population according to the different stages of lifecycle in correlation with the weather conditions (Table 3). (b) Strategy modulation at different stages of locust invasion *viz*., Outbreak prevention and upsurge prevention. While outbreak prevention, strategy makers needs to keep in mind the fact that patches of an outbreak may be distributed over a large area. Therefore, treating the locust population in blocks instead of patches using vehicle mounted ultra low volume sprayers or hand held ultra low volume sprayers will be more efficient. Hence, identification of blocks having sufficient patches must be done first. Likewise, swarm spraying was found much more efficient in comparison to hopper control to achieve better population control results (Symmons 1992). This study also pointed out that to control 5% band infestation, treating an area of 10 square km would result in prevention of a swarm of 1 square km. Despite this, most countries focus on the hopper control. However, the risk of swarm escaping always remains in this approach. (c) Understanding the swarm behaviour is also important for efficient locust population management. For instance, swarms generally fly in day till the sunset and then they remain settled throughout the night. Thus, treatment in the early morning or late afternoon (after settling) will be very effective. In contrary, hoppers do not move more than 1 km in a single day; hence they can be treated throughout the day.

Mostly, the vehicle mounted or aerial ULV (ultra- low volume) spraying is preferred for application of both chemical and microbial pesticides against locust. An ULV spraying

Table 3: Control measures to be planned in relation with different weather conditions.

Stages of development	Conditions favourable for different stages of desert locusts			Control measures
	Temperature	Wind	Rainfall	
Eggs (10–65 days)	15°C-35°C	Eggs die if exposed to wind	Laying when soil is moist 0 cm–15 cm (rainfall > 25 mm/month for 2 months)	• Identification of areas suitable for breeding. • Estimation of rate of egg development. • Planning field surveys.
Hoppers 24–95 days; average 36 days)	Air temperature range of 20°C-35°C	Band usually moves downwind	Rain needed for annual vegetation for food and shelter	• Identification of areas of green vegetation. • Estimation of rate of hopper development. • Control operations against gregarising hopper groups and bands.
Adults (2.5-5 months)	20°C-22°C	wind < 7 m/s	Mature rapidly in areas receiving fresh significant rains	• Estimation of displacement rate and direction. • Control operations against gregarising adult groups.
Swarm	Sunny conditions (15°C–17°C), cloudy conditions (23°C–26°C)	1.5–16 km/hWill not take off in winds > 10 m/s	Low pressure systems favour swarm migration	• Estimation of rate of adult development. • Estimation of displacement rate and direction. • Control operations against swarms.

assures accurate control of the droplet spectrum and adequate coverage even at the application rate of 1 liter/ hectare, which not only reduces wastages but also is prudent for environment. The list of pesticides approved by CIBRC has been enlisted in Table 4. Spraying must be done at right angles to the direction of the wind and should be stopped when wind speed drops or inflates to very strong. Otherwise, large overdose on a narrow strip of target area can possibly poison the operator. LWO are carrying out drone operations for spraying insecticides (Table 1) for rapid and targeted treatment of swarms. Use of drones or aircrafts are advocated when the target swarms are roosting or flying so that both stratiform (low flying up to100m height) and cumuliform swarms (high flying up to 1000m or more) can be sprayed with the pesticide.

Technological advancements at fao for ensuring early warning

An early warning system requires robust, elaborated and technologically advances infrastructure. The technological advancements made by FAO over this course of time have been detailed in Fig 2.

Telecommunications and computing

Initial observations made by the teams in various field surveys were in written narrative forms and further sent through postal systems, which was substantially time consuming. Moreover, the flow of information from various countries was also irregular. Thereafter, during the plague (1987-1989), FAO installed facsimile machines in order to transmit information and reports to the DLIS, which in turn sent monthly reports by fax. The data also include the information regarding rainfall, maps of surveys, locust invasion areas and forecast. Though this process had improved the data transmission and early warning systems but it was further revolutionized by the introduction of computers in late 1980s. Introduction of computers have opened endless avenues of data interpretation and data transfer. Addition of graphics, maps, images and text was now a possibility. In 1998, email and internet was introduced which replaced facsimile; enhancing the ability to rapidly, easily, timely and wide information circulation.

Geospatial data assessment

In earlier days, the longitude and latitude coordinates were plotted on paper maps manually with colored pencil, which was time and labour consuming. The naive models of GPS were also quite bulky, slow, expensive and less accurate. In late 1980s, a smaller, cheaper and more accurate handheld GPS was introduced for determining latitude and longitude coordinates of field surveys and control operations. Later, GIS (1990) with two components *viz*., database and mapping application was introduced for displaying data on maps with accuracy. In 1996, Schistocerca Warning and Management System (SWARMS) was being used by DLIS, which was modified server based GIS exclusively for managing and analyzing environmental and locust data on daily basis

(Healey *et al*., 1996). This allowed rapid access of huge data in varied formats and allowed their assessment in correlation with current weather, ecological conditions, and locust invasions. However, managing large quantities of data was a problem. To meet this issue, RAMSES (Reconnaissance and Management System of the Environment of Schistocerca) was introduced in 2000 which was more compact endless complicate. Meanwhile, GPS with accuracy within 10 m were also introduced in the year 2000.

eLocust

Despite the efforts like development of standardized forms, training of National Locust Information Officers and rapid data assessment, the weak link in early warning remained was near real-time transmission of data from the field of locust affected countries. Therefore, a digital prototype eLocust was developed for national field officers. This alkaline battery powered system has handheld Psion 5mx palmtop computer connected to GPS and database linked to mapping application. Thereafter, more sophisticate all in one system named as eLocust2 was introduced with touch screen data logger, custom language software in English and French, antenna connected to GPS satellite (for location assessment) and Inmarsat satellite (for real time data transmission). Thus, after 75 years, locust monitoring, field surveys and control impacts were instantly available for competent authority and forcasters. This system absolutely revolutionized the process of locust warning and control. Updated version named eLocust2 was introduced in 2014 with latest technology of Android-based 10.1-inch rugged Panasonic FZ-A1 ToughPad tablet. Without any internet access, it could perform landset imagery, dynamic greenness mapping and rainfall forecasting using simple wireless bluetooth. It also had digital library of references, standard operating procedures, control measures and field survey manuals.

Remote sensing

Since the early 1980s, DLIS used visible and infrared Meteosat imagery for determining clouds to produce data regarding rainfall and chances of locust breeding in Africa. However, this technique was acceptable during summer over the Sahel of Northern Africa but failed in detecting rainfall from low-level warmer clouds in winter breeding areas along the Red Sea coasts. Improvement in remote sensing imagery for detecting green vegetation occurred with consecutive onset of 7 km resolution NOAA-AVHRR and 1 km resolution imagery SPOT imagery. SOT imagery was then superseded by 250 m MODIS imagery with better resolution. Yet, the resolution was not sufficient to detect thin green vegetation,

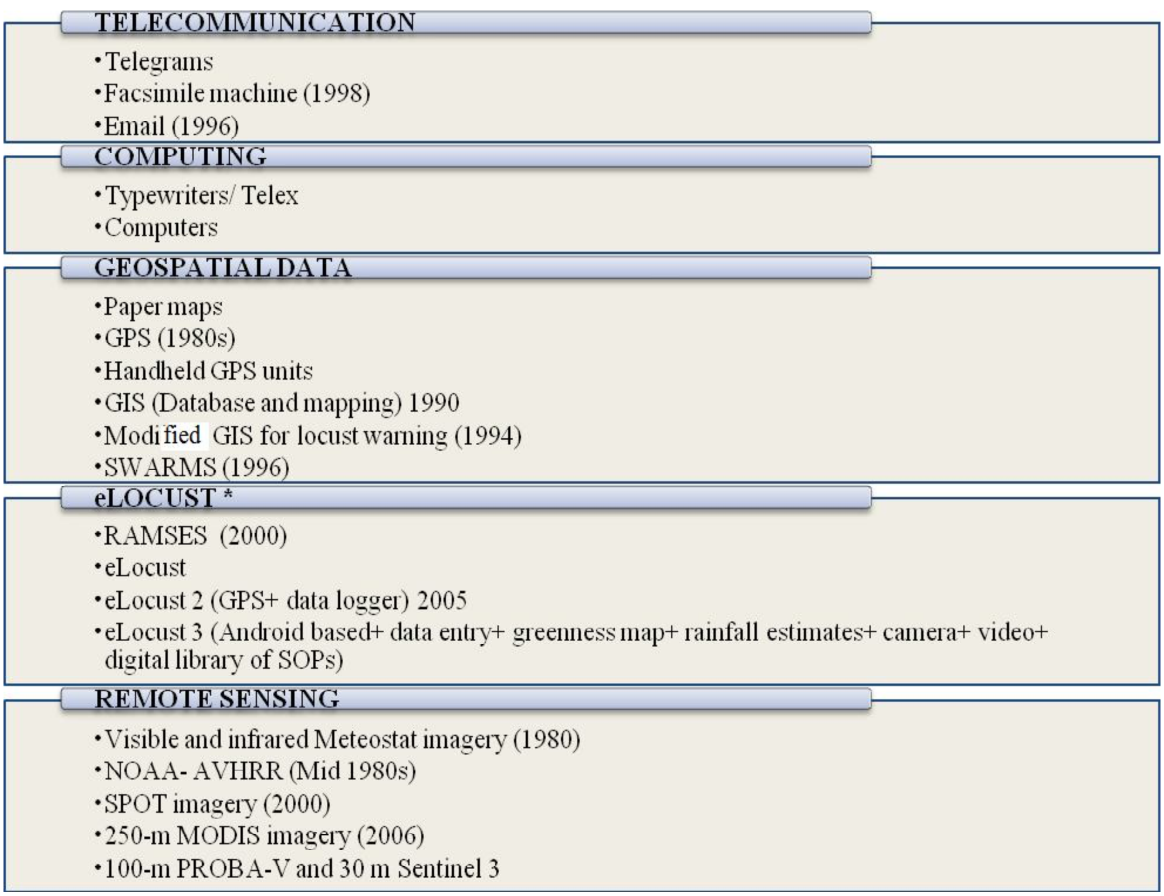

Fig 2: Schematic representation of the technological advancements of FAO for locust control

which primarily is host to the desert locusts (Dinku *et al*. 2010). Latest satellites like PROBA V and Sentinel 3 offer better detection of green vegetation with resolution up to 100 m and 30 m, respectively.

Challenges in swarm outbreak management

Generally, the outbreaks of the desert locust are episodic having alternating periods of invasion and recession. Locusts are a challenge to control because of their high mobility (50-100 km/day), uneven distribution and irregular incidences of upsurges. The issues to be considered while managing desert locust population include: (a) impact of control failure in one area on others. Since, locust invasion is characterized by speedy migration; the efficacy of locust population management across the varied areas is inter-linked. Past experiences stamps on the fact that effective preventive control operations could not be carried out in whole distribution areas of desert locust as few of those areas were too remote, insecure and located in countries where control units exist in name only. International issues like conflicts between countries also decrease the efficacy of field surveys and control measures. For efficiently controlling the locust upsurges, the network of local, national and international bodies has to work in an integrated way. (b) Real costs of detecting and controlling early upsurges throughout recession area are too costly to be feasible, especially for poor and developing countries. (c) Use of massive insecticides over a large landscape affects biodiversity including non- target arthropods. Also, the idea is to control the populations rather eliminating them from an ecosystem. The areas where densities often exceed thousands per square meter usually control up to 95%-98% is required (Latchininsky *et al*. 2002). Since, they are important part in food chain; the pesticide residue in locusts may lead to bio-magnification at higher trophic levels leading to negative impact on human health. Further, in remote areas especially in Africa, the tribal people depend on the local vegetation for fodder of their livestock. After spray of insecticides over them to control locusts, they become unfit for animal consumption and this adds to their struggle. Hence, locusts invasions in past had triggered intensive global research efforts to develop safer synthetic insecticides which are less hazardous to the environment and not target species. Though the bio-pesticides are environmentally safe, the potential of bio-pesticides is under explored and unused still. The possible long-term measures for locust risk management at different levels have been summarized in Fig 3.

Multitude approach for locust control: prospects of further research

It is evident from the previous studies that human activities can alter the locust population dynamics just by managing the land (Cease *et al.* 2015). Heavy livestock grazing

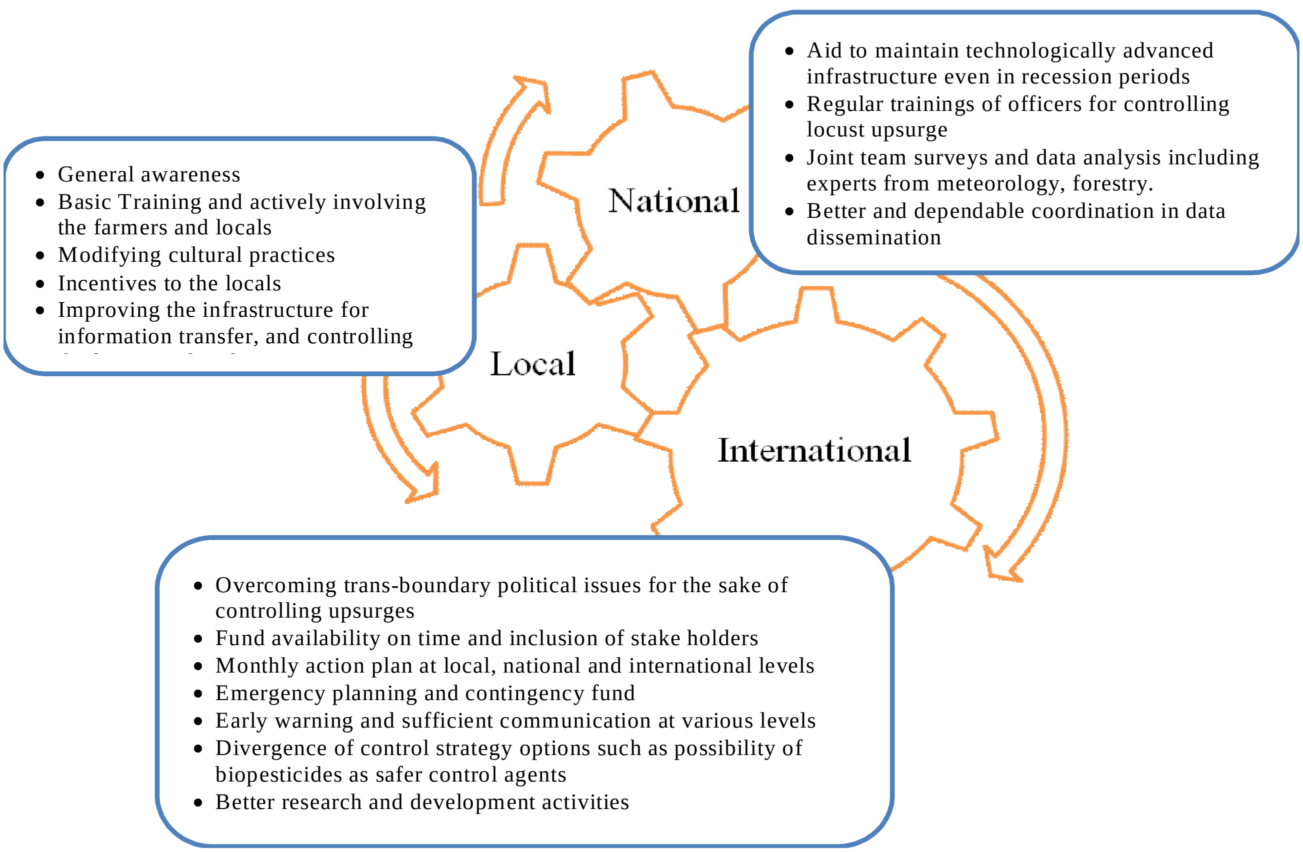

Fig 3: Possible long term measures for the risk management systems at different levels

Table 4: List of various approved pesticides for control of desert locust in India.

Chemical	Dosage		
	a.i. (gms/ha)	Formulations (gm/ml)/ha	Dilution in water (litres/ha)
To be used in scheduled desert area only			
Malathion 96%ulv	925	1000	NA
Malathion 5% DP	925	20000	NA
Fenvalrate 0.4% DP	80-100	20000-25000	NA
Quinalphos 1.5% DP	375	25000	NA
To be used on crops, acacia and other trees			
Chlorpyrifos 20%EC	240	1200	500
Chlorpyrifos 50% EC	240	500	500
Deltamethrin 2.8% EC	12.5	500	500
Deltamethrin 1.25% ulv	12.5	1000	N/A
Diflubenzuron 25% WP	60*	240	Need base
Fipronil 5% SC	6.25	125	500
Fipronil 2.92% EC	6.25	220	500
Lamdacyhalothrin 5% EC	20	400	500
Lamdacyhalothrin 10%WP	20	200	500
Malathion 50% EC	925	1850	500
Malathion 25% WP	925	3700	500

*Only for hoppers control (Source: CIBRC, List of approved Pesticides for control of Desert Locust).

practices in the region of Mongolia results in low plant nitrogen content thus makes the ecosystem more susceptible to Mongolian locust (*Oedaleus asiaticus*) outbreak (Cease 2012). Despite the known positive impact of excessive livestock grazing on the locust populations (Branson *et al*. 2006), the management of locust populations through land management practices have received little attention (Gall *et al*. 2019). Likewise, change in land use may also lead to the change in pest status of other species too. For instance, the introduction of European livestock and agriculture to Australia has supposedly promoted the Australian plague locust, *Chortoicetes terminifera* in late 1800's (Deveson 2012). The significant decrease in locust population in small farms due to increased organic matter in West Africa has also been reported (Word *et al*. 2019). Thus, multitude approach of understanding livestock-locust interactions forms a potential area for the further research to solve the existing food security threats imposed due to locust's outbreak. Reduced survival and reproduction rate has been evident in habitat alterations (Branson *et al*. 2006). The impact of increase in the population of natural enemies of grasshoppers/locusts is still among the unexplored avenues of locust management. Further, the role of pheromones and semiochemicals in swarm formation is unclear. While the bio-control agents like *Metarhizium* and *Paranosema* are commercially available, there is a possibility of discovery of more potential virulent and stress resistance strains using selection and gene modification method (Wang and Kang 2014). The prospective of other microorganisms like bacteria, virus and nematodes are still unexplored. Likewise the holistic approach including efficacy of plant extracts and the novel nano-formulations (Liu *et al*. 2016) needs to be understood better to reduce the impact on environment.

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