European Journal of Ecology, 9.2, 2023, pp. 52-66

PREFERENTIAL SOIL CONDITIONS FOR THE OVIPOSITION OF DESERT LOCUST (*SCHISTOCERCA GREGARIA*): GEOSPATIAL ANALYSIS

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Abstract.

*Understanding the thresholds of influencing parameters that favor the habitability of dangerous pests like desert locusts (*Schistocerca gregaria*) can aid in early detection and eradication using control operations. The life cycle of the desert locust and its behavioral changes are associated with the weather patterns and the region's ecosystem settings. This study attempts to retrieve the preferential soil conditions like texture and moisture at the surface and subsurface levels for egg-laying by desert locusts. Towards this, Locust Hub, a comprehensive database of desert locusts maintained and disseminated by the Food and Agriculture Organisation under the Locust Watch program, has helped identify the locations of breeding sites reported during 2017-2021. We have extracted sand-silt-clay percentage at these breeding sites using SoilGrids ver. 2.0 from the World Soil Information Service database facilitated by International Soil Reference and Information Centre. Similarly, soil moisture conditions extracted from Level-4 data products of the Soil Moisture Active Passive mission for all these breeding sites aided in essaying the optimal soil conditions for the desert locust's oviposition. The results from this study confirm that successful oviposition has happened in the locations where the sand percentage is in a broad range of 55-70% (for 90% of samples), followed by a narrow range of silt and clay with 19-24% and ~14-20%, respectively. Our experiment has revealed that female desert locusts prefer sandy loam-textured soils for oviposition. Also, it is observed that the female desert locust will prefer soils with moisture at the surface and subsurface in the range of 5-10% and 10-20%, respectively. These results confirm that dampness is required at the surface soil for initiating the oviposition by female desert locusts. Results from this research can aid in the early identification of breeding grounds during desert locusts' invasion period. Our study fills a vital gap in understanding the desert locust ecology and can be a part of the framework connecting locust systems and food security issues.*

Key Words: *Desert locust, oviposition, breeding, soil texture, soil moisture, SoilGrids 2.0, Soil Moisture Active Passive mission, Earth Observation systems, geospatial technology*

Introduction

A locust is a grasshopper species but differentiated by its larger size and is characterized by gregarious habits; historically, it has exhibited episodic tragic tales of devastation leading to large-scale food security issues (Uvarov 1943; Showler 2019). The recent plague due to the desert locust (*Schistocerca gregaria*) of spring 2020 in East Africa is termed an ancient type by Worboys (2022). Cullen *et al.* (2017) reviewed the evolution and diversity of swarming grasshoppers and reported 19 species considered actual locusts. Out of these 19 species, the desert locust is one of the model species that exhibits a complete suite of traits associated with actual locust behavior. Desert locusts can congregate as dense migration swarms through an extreme form of density-dependent phenotypic plasticity known as locust phase polyphenism (Song *et al.* 2017). Managing the desert locust poses vast challenges and is costly due to its variable phenotypes associated with behavior, morphology, and physiology (Le Gall *et al.* 2019); thus, there is a need for a better understanding of its characteristics and supportive environmental settings. Symmons and Cressman (2001) reported comprehensive details of desert locusts, which included their biology, behavior, life cycle, grouping patterns (hopper to bands and adults to swarms), phases of polyphenism (solitarious and gregarious), and patterns of infestation (recession, outbreaks, upsurges, and plagues).

Due to the desert locusts' ability to reproduce rapidly and long-distance migration, and their voracious appetite, numerous incidents in the past witnessed the devastation to the crops (Krall & Herok 1997). It is necessary to control and combat its natural habitability in over 30 countries (specifically, in arid and semi-arid regions). For this, the United Nations Food and Agriculture Organization (UN FAO) operates a global early warning system by harnessing the latest technological advances that have helped better analyzing and forecast outbreak situations (Cressman 2016).

However, entomologists are putting significant efforts into understanding better details associated with the desert locusts' behavior, ideal habitat ecology, and their reciprocation with the environmental conditions. Earth Observation (EO) systems, geospatial technologies, numerical weather forecast data, drones, and machine learning concepts are effectively being used to monitor and manage desert locusts (Cressman 2013; Latchininsky 2013; Gómez *et al.* 2018; Ellenburg *et al.* 2021; Matthews 2021). In recent years, researchers have harnessed the potential of EO-based and numerically computed weather data that is made available as free and open access, which can be used to perform studies on desert locusts (Gómez *et al.* 2019; Wang *et al.* 2021).

The life cycle stages of the desert locust (breeding, egg-laying, egg development, hoppers, adults, and swarms) and its behavioral changes are highly associated with the weather patterns and ecosystem settings (Pedgley & Rainey 1979; Latchininsky *et al.* 2011; Cressman & Stefanski 2016). The weather parameters that act as drivers for desert locust habitats are precipitation, temperature, and wind. Precipitation influences the moisture conditioning in the soil and also on the vegetation. The availability of moisture in the soils of arid and semi-arid regions can trigger the reproduction potential of desert locusts since the female needs moist areas to lay the eggs (Escorihuela *et al.* 2018). The survival of desert locusts and their gregarization phenomenon is usually guided by vegetation availability (Despland *et al.* 2000; Cressman 2013). Specific temperature ranges influence the desert locusts' growth and development during the instar stages, egg development, maturity, movement, and swarm take-off (Cressman & Stefanski 2016). The wind settings catalyze the desert locusts' movement and migration (Kennedy 1951; Dandabathula *et al.* 2020).

Previous researchers have reported the optimal environment and weather conditions for various instar development and adult habitats (Pedgley & Rainey 1979; Symmons & Cressman 2001; Latchininsky *et al.* 2011; Cressman & Stefanski 2016). In this research, we intend to understand the optimal soil parameters like texture, moisture, and temperature for desert locusts' breeding sites. Soil conditions at the root zone also play a vital role in the desert locust egg-laying strategy. Thus, recording the surface and subsurface soil parameters preferred for egg-laying by desert locusts is pertinent. This research uses two open-access data sets to derive these soil parameters, specifically at desert locusts' breeding sites. One is a global gridded soil information developed using machine learning techniques, and the other one is EO-based Soil Moisture Active Passive (SMAP) mission that measures and maps Earth's soil moisture.

Brief Background About Desert Locusts' Egg-Laying Strategy

Female desert locusts can accurately sense the preferred soil conditions for successful egg-laying and development (Ferenz & Seidelmann 2003). Towards this, the female locust will probe the soil by inserting the tip of her abdomen to determine the required moisture conditions (Symmons & Cressman 2001). On the successful determination of the favorable conditions, egg production in a clustered fashion called egg-pods with a typical size of 3-4 cm containing up to 120 eggs is possible (Symmons & Cressman 2001; Latchininsky 2013). During the oviposition, female locusts' abdomen can penetrate up to a ground depth of 2-15 cm (the root zone) for successful egg laying (Piou *et al.* 2019; Ellenburg *et al.* 2021).

Locust eggs (Fig. 1) are coated by a foamy material which aids in hardening into a membrane and plugs the hole above the egg pod (Van Huis *et al.* 2007). The eggs absorb the moisture in the soil subsurface during their development (Mariod *et al.* 2017). The incubation period, ranging from 10 to 65 days, depends on the temperature and moisture of the egg-pod's surroundings. Lack of moisture may arrest the egg development, and at certain times desiccation of deposited eggs happens if the temperature is not supported (Woldewahid 2003). Our study takes advantage of the space-borne sensor capability of essaying the soil moisture and further correlates with the ecological conditions during desert locust oviposition; thus, the obtained results should provide a good understanding of this vital life cycle event of desert locust, which can aid in filling gap areas in understanding the locust system ecology.

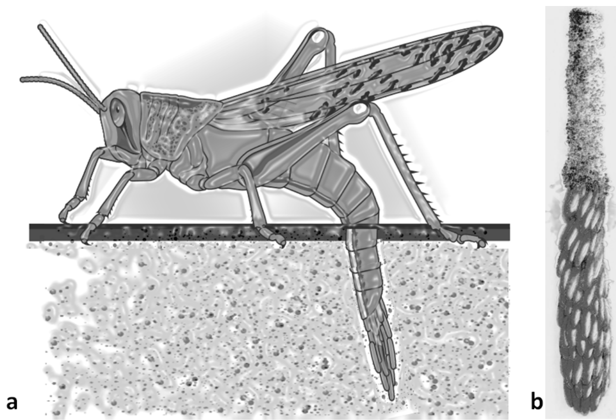


Fig. 1 Oviposition of female desert locust and its corresponding egg-pod. (a) Oviposition, in which the abdomen of female locust penetrates the subsurface. While the egg is being released, the abdomen can expand up to 15 cm. (b) A typical egg-pod of a desert locust resembles a cluster of rice grains and is arranged like a small hand of bananas.

Materials and methods

Datasets

Under normal conditions, desert locusts will predominantly persist in the arid and semi-arid regions spread throughout the deserts of North Africa, the Middle East, and Southwest Asia (Cressman 2016). However, the plague can affect nearly 55 countries (Tucker *et al.* 1985; Wilps 1997; Van Huis *et al.* 2007). In this study, we have considered the frequent invasion areas of desert locusts to collect the egg-laying sites; this includes countries in North Africa, the Middle East, and Southwest Asia.

Desert Locust Information Service (DLIS) is operational by FAO that monitors the global desert locust situation, providing forecast information, early warning, and alerts along with the location information of the invasions and breeding sites (DLIS 2022). Under the aegis of DLIS, all the related departments/institutes of locust-affected countries provide field-level information to FAO, which in turn analyses the data in conjunction with weather and remote sensing methods to assess the locust situation at the global level. FAO shares the accumulated field-level data with the shareholders through a GIS-enabled web portal, Locust-Hub (Locust-Hub 2022). Datasets about the locations of hoppers, bands, adults, swarms, and the details of control operations are disseminated through this web portal in the form of GIS-ready formats like shape files.

This research retrieved data about hoppers and adult breeding sites from the Locust-Hub (2022) for 2017-2021. The rationale for selecting this period is that during 2018-2021, there was a desert locust upsurge (FAO 2021). Cyclones in May and October of 2018 brought heavy rains that gave rise to favorable breeding conditions in the Empty Quarter of the southern Arabian Peninsula for at least nine months. Due to this, three generation of breeding occurred that was undetected and uncontrolled; from 2019 onwards, a massive outbreak of desert locust swept across the greater Horn of Africa and Yemen by reproducing the desert locust exponentially (Dandabathula 2020; Sultana *et al.* 2021). 441 and 3725 breeding sites were accumulated for hoppers and adults from the Locust-Hub (2022) database. Fig. S1 shows a spatial map depicting the locations of desert locusts' egg-laying sites aggregated during 2017-2021.

Observation from the aggregation of desert locusts' egg-laying sites confirms the dominant locations for egg-laying in border regions of Uganda and Kenya, Eritrea, Djibouti, Somalia, Ethiopia, Kenya, Chad, Sudan, and Jordan. Earlier, researchers like Bennett (1976), Pedgley and Rainey (1979), Ellenburg *et al.* (2021), Klein (2021), and Wang *et al.* (2021) confirmed the existence of breeding sites in these locations. Similarly, most of the Thar Desert region that spread over the India-Pakistan border supports egg-laying activity for desert locusts. Extensive work done by Rao (1942) in the Thar desert region confirms the egg-laying activity and the same is evident in Fig. S1, where significant incidents of locust breeding sites are observed during 2017-2021.

International Soil Reference and Information Centre (ISRIC) provides open access to global soil data under World Soil Information Service (WoSIS). A dedicated web portal titled SoilGrids 2.0, available at (https://soilgrids.org) enables users to visualize and access the data. WoSIS provides global gridded soil data at 250 m resolution at six standard depths (viz. 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm, and 100-200 cm). These datasets were prepared using machine learning techniques by ingesting soil observations from 240,000 locations worldwide and over 400 environmental covariates describing vegetation, terrain morphology, climate, geology, and hydrology. SoilGrids 2.0, containing the global soil maps, were built based on previous work by Hengl *et al.* (2017) under the title SoilGrids250m. These datasets are available as world mosaics in the Virtual Raster Tile (VRT) format from the web portal (https://files.isric.org/soilgrids/latest/) maintained by ISRIC. In this study, we have retrieved mean values of sand, silt, and clay at 0-5 cm (surface) and 5-15 cm (subsurface) depths, respectively. Table 1 contains the details of the VRT files used in this study.

Fig. S2 shows a subset of the global soil map (sand constituent at 0-5 cm) from SoilGrids ver. 2.0 for the ex-

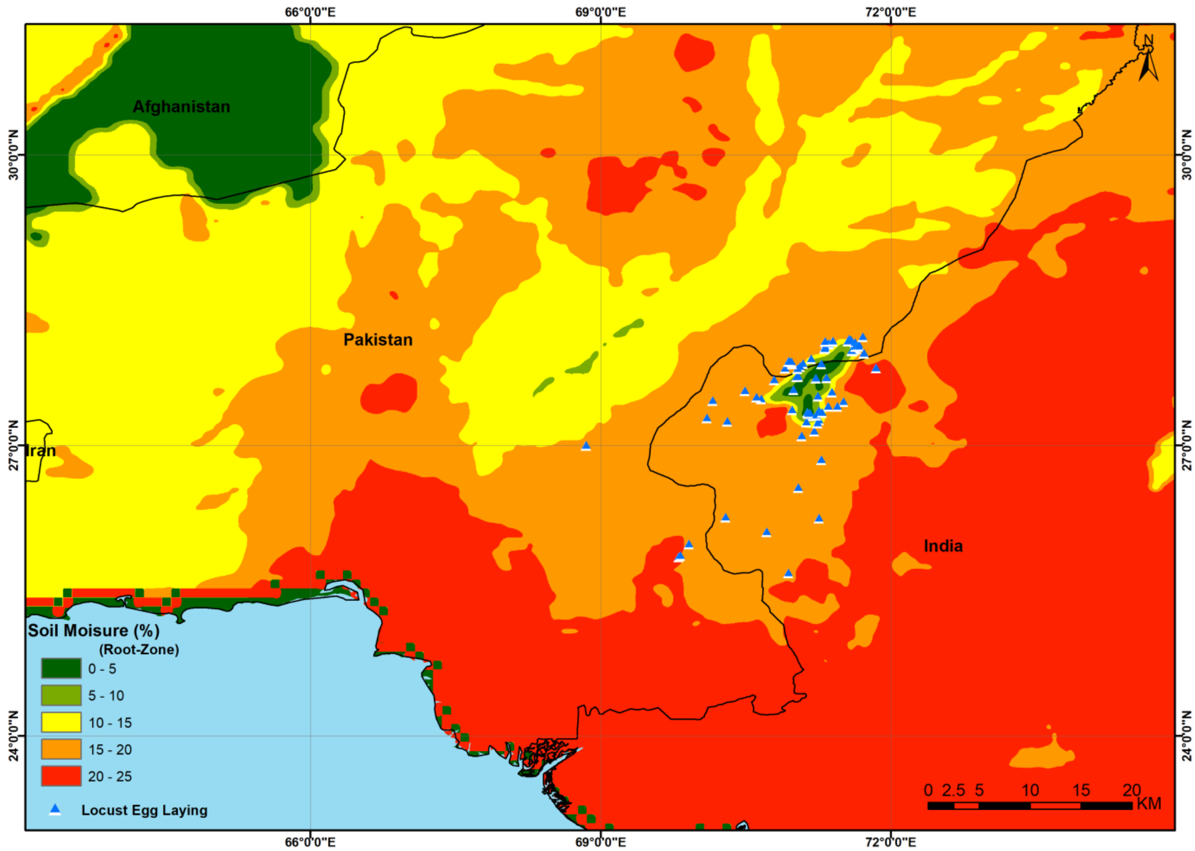


Fig. 2 Map showing a subset of global SMAP L4 product representing the soil moisture at root zone during August 2019 for the extent of the Indo-Pakistan border region overlaid with the egg-laying sites reported during the same period. Note the occurrence of egg-laying sites that are dominantly preferred in regions with soil moisture (at subsurface) in the range of 5-15%.

tent of the desert locust invasion area. Due to arid and semi-arid zones, sand's content is usually higher in this area. Earlier, Ellenburg *et al.* (2021), Sun *et al.* (2022), and Klein *et al.* (2022) utilized the data resources from SoilGrids ver. 2.0 in their respective studies related to the desert locust.

Soil Moisture Active Passive (SMAP) mission is a space orbiting observatory from the National Aeronautics and Space Administration (NASA) that measures the soil moisture on Earth (Entekhabi *et al.* 2014). The SMAP Level 4 (L4) product provides 3-hourly, 9 km resolution global estimates of soil moisture at the surface (at 0-5 cm) and root zone (at 5-100 cm) along with related land surface variables by assimilating space-based observations and numerical modeling (Reichle *et al.* 2017). This study retrieved soil moisture at the surface, root zone, and land surface temperature of the desert locusts' breeding sites from SMAP L4 products corresponding to the reported egg-laying period. Earlier, Gómez *et al*. (2019) utilized soil moisture information from SMAP L4 data products for desert locust studies. SMAP L4 data products are available from the portal maintained by National Snow and Ice Data Centre (NSIDC-SMAP 2022). More details about SMAP L4 are given by Reichle *et al.* (2021). Fig. 2 shows a subset of global SMAP L4 representing the soil moisture at the root zone during August 2019 for the extent of the Indo-Pakistan border region overlaid with the egg-laying sites reported by FAO (Locust-Hub 2022) during the same period.

Methodology

Fig. 3 represents the methodology used in this study. A total of 4166 (441 for hoppers and 3725 for adults) breeding sites of the desert locusts were retrieved for 2017-2021 from the FAO's Locust-Hub web portal. For these sites, the mean content of sand, silt, and clay was taken from SoilGrids ver. 2.0 at the surface (0-5 cm) and subsurface (5-15 cm) for a buffered region of 2 km. The rationale for selecting a buffer region of 2 km is that the congregation of the desert locust can extend for more than 1 km (Jones 2016). Similarly, mean soil moisture at the surface and root zone and the mean land surface temperature were retrieved using SMAP L4 data products for a buffered region of 2 km. The interpretations of these results were discussed in the subsequent section. Field visits to ascertain our results were carried out and Fig. 4 shows the photographs acquired during the fieldwork.

Table 1 Summary of the datasets utilized towards detecting the preferred soil conditions for egg-laying by desert locusts.

Datasets	Source of datasets	Remarks/Relevancy
Desert locust egg-laying locations	Locust Hub database (Locust-Hub 2022) with the records satisfying the condition ‘breeding=1’.	441 and 3725 breeding sites were aggregated from the Locust-Hub data for hoppers and adults, during 2017-2021. These locations were converted to the spatial domain and further used to infer the soil conditions.
Sand, silt, clay content at surface (0-5 cm)	Sand: sand_0-5cm_mean.vrt Silt: silt_0-5cm_mean.vrt Clay: clay_0-5cm_mean.vrt The above virtual raster are available at WoSIS (2020) in g/kg units.	Virtual raster files were converted to TIF format using GDAL libraries. These datasets were used to infer the surface soil composition details at all the breeding sites of the desert locust.
Sand, silt, clay content at subsurface (5-15 cm)	Sand: sand_5-15cm_mean.vrt Silt: silt_5-15cm_mean.vrt Clay: clay_5-15cm_mean.vrt The above virtual raster are available at WoSIS (2020) in g/kg units.	Virtual raster files were converted to TIF format using GDAL libraries. These datasets were used to infer the subsurface soil composition details at the breeding sites of the desert locust.
Soil moisture at surface and root zone	SMAP Level 4 data products available at NSIDC-SMAP (2022).	Soil moisture geophysical data, version 6, was used to retrieve moisture conditions at the surface and root zone for all the breeding sites of the desert locust for their reporting period.
Land surface temperature	NSIDC-SMAP (2022).	The Land surface temperature was retrieved from NSIDC-SMAP (2022) for all the breeding sites for the reporting period.

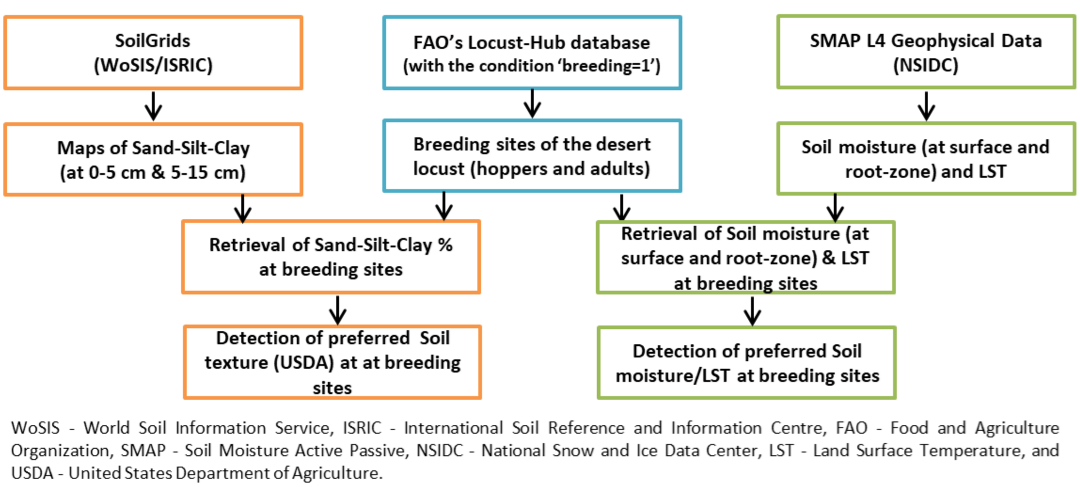


Fig. 3 Methodology implemented to derive soil parameters like texture and moisture at the locations of desert locusts’ breeding sites.

Fig. 4. Field photograms at Gamnewala village near Jaisalmer – a city in the Thar desert region, India. (a) The Photograph was taken on 11 November 2019, showing a female desert locust in oviposition. (b) The photograph taken on 03 March 2022 shows the capability of preserving dampness in the subsurface by the sandy loam soils in the Thar Desert region. (c) A typical landscape where female desert locusts congregated for oviposition near Gamnewala village during November 2019. Typically these sorts of landscapes were also preferred habitats for mammalian fauna, like the hairy-footed gerbil (*Gerbillus gleadowi*); notably, the burrows can be seen in this field photo.

Results

Sand-silt-clay content at the surface and subsurface soils of desert locusts' breeding sites

Fig. 5 shows the relationship obtained for the content of sand, silt, and clay with respect to the number of desert locusts' breeding sites at the surface (0-5 cm) and subsurface (5-15 cm) soils. It is observed that predominantly these breeding sites have a dominant constitution of sand followed by silt and clay at both the surface and subsurface. The mean values of sand, silt, and clay content (g/kg) at the surface of all the breeding sites (n=4199) at the surface are ~600, ~220, and ~170, respectively - similar values observed at the subsurface of these breeding sites. Table 2 shows the range of sand, silt, and clay constituents at the surface and subsurface. Notably, the pattern of the breeding site's sand, silt, and clay constituents is similar for hoppers and adults.

Fig. 5. Relationship obtained for the content of sand-silt-clay at the surface soils (0-5 cm) and subsurface (5-15 cm) with respect to the percentage count of desert locusts' breeding sites. The charts contain the percentage of the number of breeding sites of desert locusts on the y-axis and the content of sand/silt/clay (g/kg) on the x-axis. (a, b) Chart for sand content at the surface and subsurface. (c, d) Chart for silt content at the surface and subsurface. (e, d) Chart for clay content at the surface and subsurface.

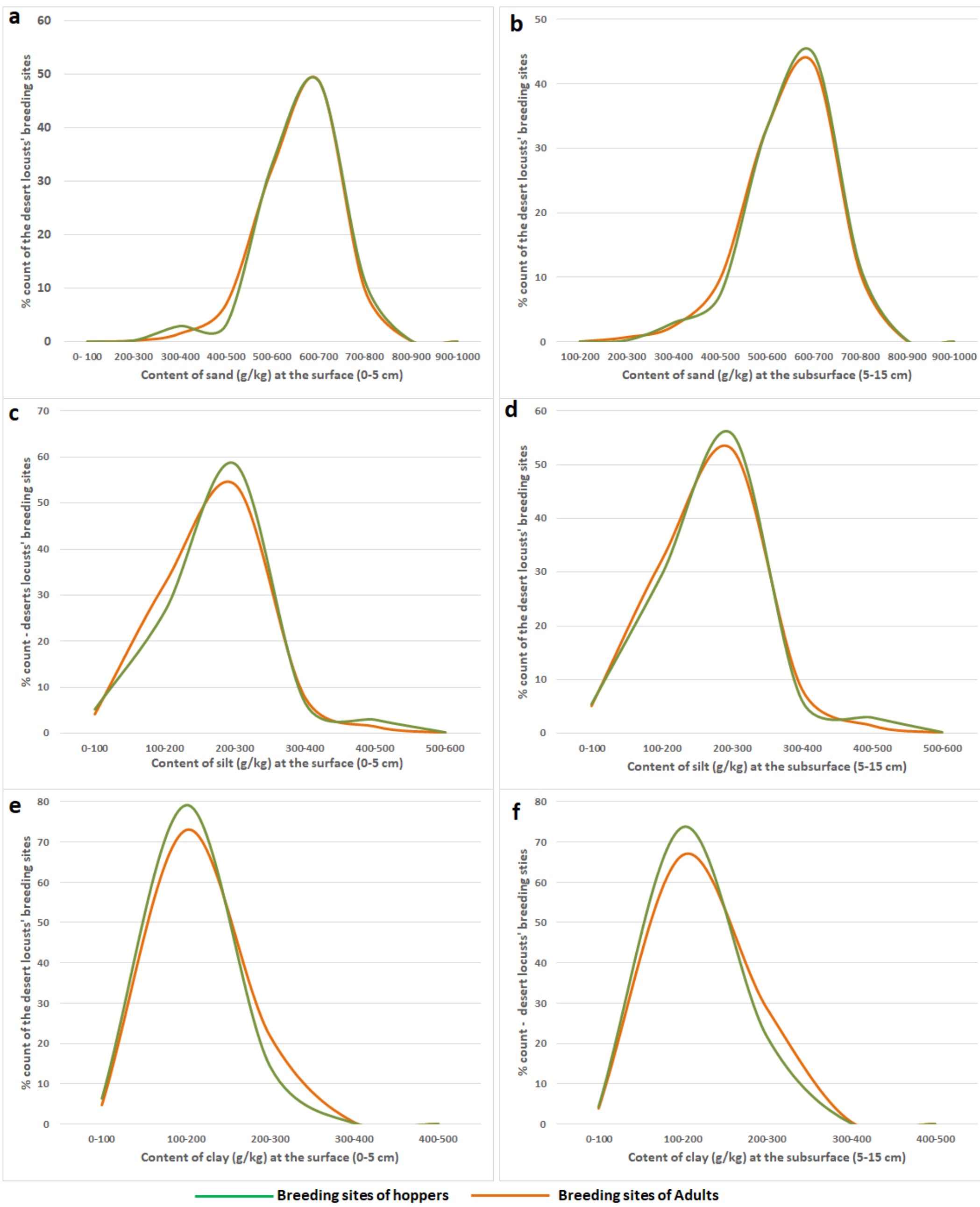
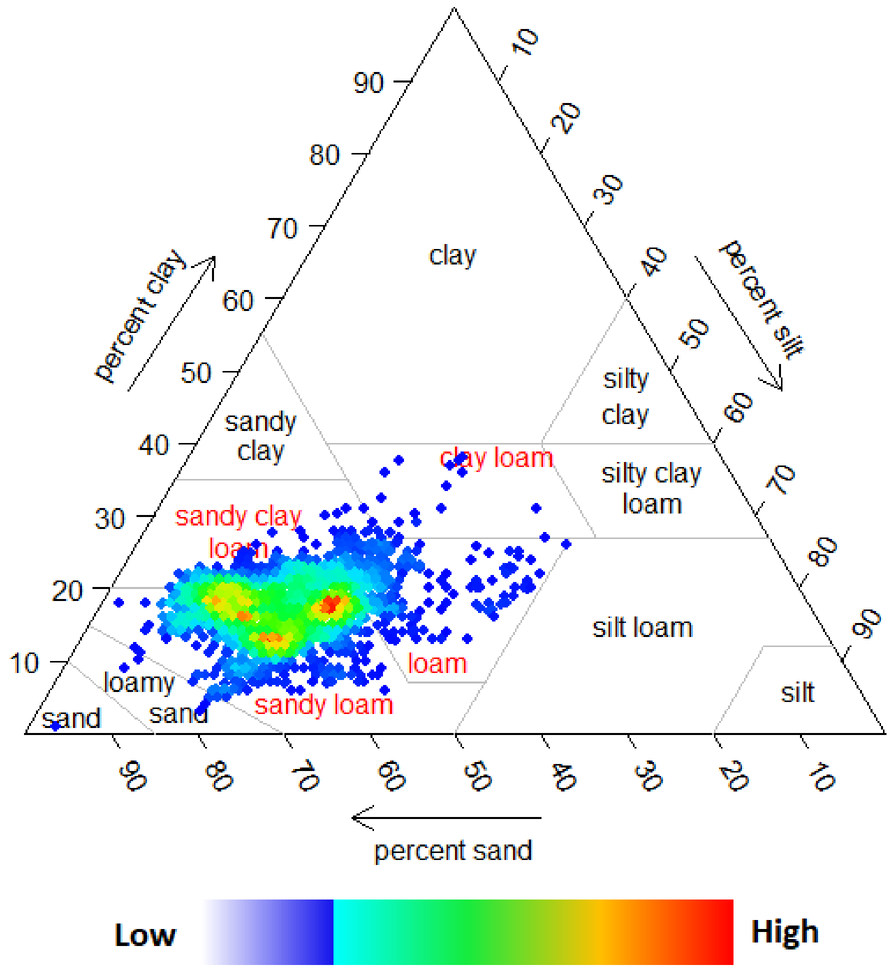


Fig. 6 Density map generated on USDA soil triangle using the values of sand-silt-clay percentage at the desert locust breeding sites. ~90% of 4166 locations of desert locusts' breeding sites fall in sandy loam soils.



With the values derived for sand, silt, and clay percentage, soil texture class at all the 4166 breeding sites have been generated based on the United States Department of Agriculture (USDA) soil classification triangle (USDA-NRCS 2022). At the outset, ~90% of these 4166 breeding sites fall into sandy loam soils, this is evident in Fig. 6 - which shows the density map generated from sand-silt-clay percentages for all the breeding sites overlaid on the USDA soil triangle.

Soil moisture (at surface and root zone) and land surface temperature at desert locusts' egg-laying sites

Fig. 7 shows the relationships obtained for the soil moisture (at the surface and subsurface) and land surface temperature with respect to the number of desert locusts' egg-laying sites, respectively. The charts indicate that the breeding sites have more soil moisture at the root zone than soil moisture at the surface (may be due to evapotranspiration). ~90 percent of breeding sites prefer locations with soil moisture at root zone in the range of ~11-20% and the range of land surface temperature being ~25-45 °C. Here, the breeding site's soil moisture preference pattern is similar for hoppers and adults. Table 2 includes the range of preferred soil moisture and temperature conditions for desert locusts' breeding sites.

Fig. 7 Relationship obtained for the soil moisture (at the surface and root zone) and land surface temperature with respect to the number of desert locusts' breeding sites. These charts contain the percentage count of desert locusts' breeding sites on the y-axis. (a) X-axis with soil moisture (%) at surface soil. (b) X-axis with soil moisture (%) at subsurface soil. (c) X-axis with land surface temperature (°C) at surface soil. It is evident from these graphs that desert locusts prefer sites with more subsurface soil moisture than surface soils for oviposition.

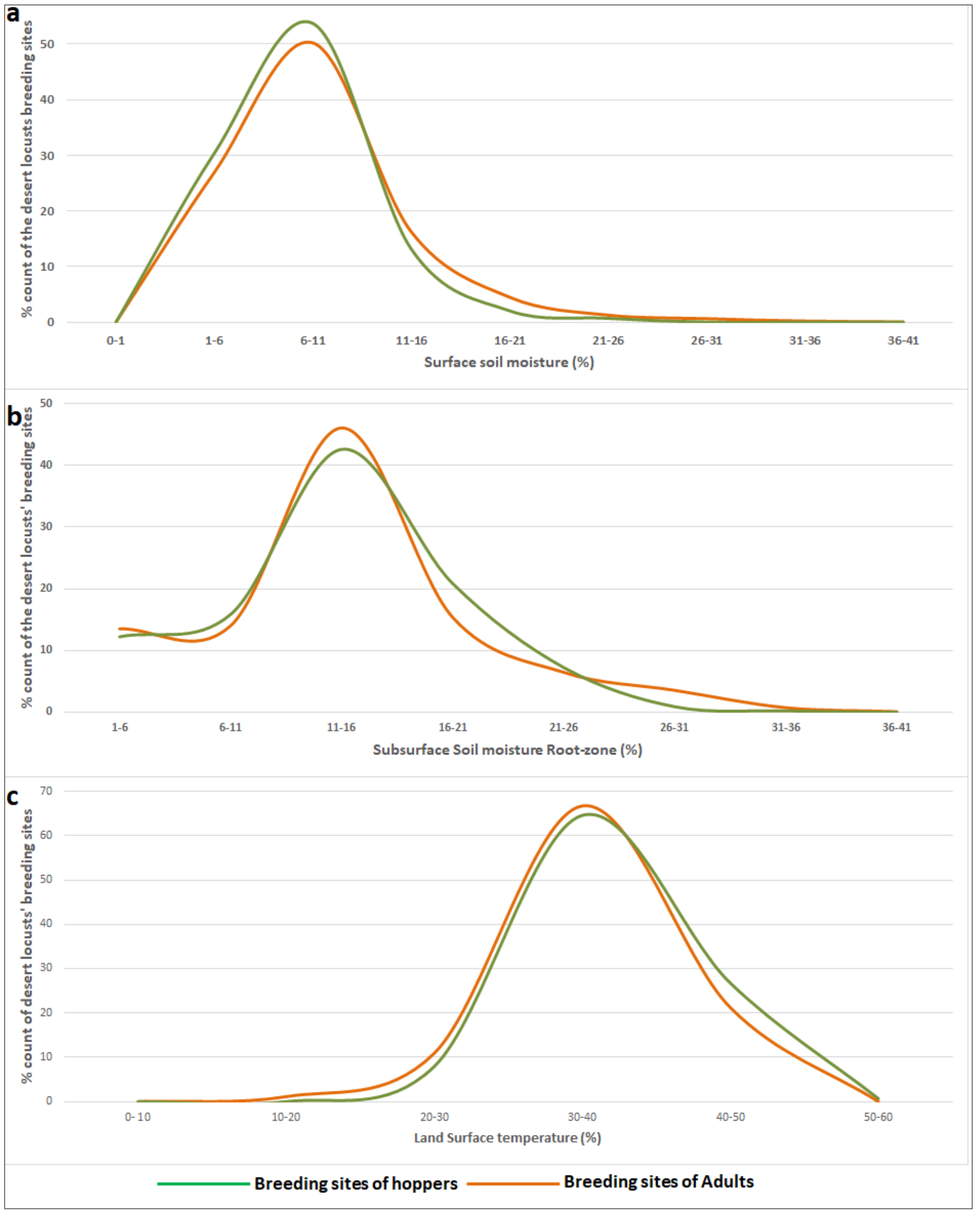


Table 2. Summary of the preferred range of sand-silt-clay percentage at surface and subsurface, soil texture classes, soil moisture (at surface and root zone), and land surface temperature for 4116 sampled locations of desert locusts' egg-laying sites.

Soil Parameter	Soil sub-parameter	Preferred range by 90% of breeding sites
Surface Soil (0-5 cm)	Sand Silt Clay	550-670 g/kg 190-240 g/kg 140-200 g/kg
Subsurface Soil (5-15 cm)	Sand Silt Clay	540-660 g/kg 195-245 g/kg 145-205 g/kg
Percentage of egg-laying locations falling in various soil texture classes (n=4116)	Sandy loam Sandy clay loam Loam	80% 11% 9%
Surface soil moisture	--	5-10 %
root zone soil moisture	--	10-20 %
Land surface temperature	--	25-45 °C

Discussion

The importance of soil texture concerning the desert locusts' egg-laying strategy lies in the fact that the female locusts' abdomen has to penetrate the subsurface permitting the posture for oviposition. Further, the subsurface soil should retain sufficient moisture for egg development. For this, the female desert locusts will probe the soil by inserting the tip of the abdomen to a certain extent of subsurface soil. Notably, the female-selected egg-laying site ensures a rigid excavation, preventing the walls of the hole from collapsing on the eggs and egg desiccation (Gaaboub 2008). Thus, it prefers damp soil with the right mix of sand, silt, and clay. Popov (1958) and Katiyar (1960), while studying the oviposition patterns of various Acrididae, observed that the preference for the soil is so great that in many cases, the female desert locust was observed feeling quite miserable on unfavorable soils due to heavyweight in their ovaries; under such conditions, they either drop their eggs on the soil surface or stop taking food and ultimately die without oviposition.

From the analysis done in this study, approximately 90% of the breeding sites have sand percentages in a range of 55-67%, whereas the silt and clay percentages are very narrow in order, ~19-24 % and ~14-20 %, respectively. All the 4166 breeding sites in this study broadly fall into the soil texture classes like sandy loam, sandy clay loam, and loam. Nearly 80% of these points are in sandy loam, indicating that female desert locusts prefer moderately coarse texture soils. Observations from the field and lab experiments by Rao (1942) related to desert locusts in the parts of the Thar Desert region concluded that female desert locusts would deposit the eggs in relatively soft sandy or loam soils. Ellenburg *et al.* (2021), while studying the patterns of desert locust breeding sites in Eastern Africa with a particular focus on the countries like Eritrea, Djibouti, Somalia, Ethiopia, and Kenya, confirmed these sites with higher sand percentages. Our results are in line with the observations made by Rao (1942), Mohammed *et al.* (2015), and Ellenburg *et al.* (2021) in connection with soil texture conditions.

Analysis of soil pH at 4166 locations of desert locusts' breeding sites in this study resulted in obtaining values ranging between 7.1 to 8.5 (90% of samples). This range of soils is slightly alkaline to moderate alkaline. Earlier researchers have not discussed the information about desert locusts' breeding site preference toward soil pH.

During oviposition by the female desert locust, it prefers the moist soil at the surface and subsurface (Tucker *et al.* 1985; Symmons & Cressman 2001; Piou *et al.* 2019) so that it can provide the rigidness for excavation of holes for egg-laying (Gaaboub 2008). Thus, the female desert locust will probe for moisture availability on the surface and subsurface. However, the importance of soil moisture in the subsurface is a critical parameter for egg development (Symmons & Cressman 2001). Soil moisture at the surface and subsurface of the desert locusts' breeding sites resulting from this analysis are 5-10% and 10-20%, respectively, for 90% of the samples. These results confirm that dampness is required at the surface and subsurface soil for initiating the oviposition by female desert locusts. Earlier, Popov (1958) and Hunter-Jones (1964) observed that female desert locusts prefer sandy substrates with moisture between 5-25%; our results are in line with the observations made by these researchers.

Studies by Kimathi *et al.* (2020) highlighted the importance of surface temperature as a critical factor during the oviposition by desert locusts. The probing activity by the female desert locusts during the breeding period includes the preference for warmer temperatures and open sites for initiating the digging activity. Our study observed that the optimal land surface temperature range during oviposition occurred at 25-45°C (for 90% of the samples) and confirmed the persistence of warmer temperatures during the egg-laying period. The observation obtained from this analysis with respect to land surface temperature is similar to that reported by El-Hadi (1966) through field investigations.

Field investigations in the Thar Desert region of the Indian side done during the invasion period (November 2020) and also during March 2022 yielded interesting observations that most of the preferred breeding sites of desert locusts are preferred sites for mammalian fauna like the hairy-footed gerbil (*Gerbillus gleadowi*) and the Indian desert jird (*Meriones hurrianae*). The literature description provided by Prakash and Jain (1971), Prakash *et al.* (1971), Prakash (1974), and Idris (2009) confirm that similar soil conditions are preferred to make burrows by this mammalian fauna. However, this aspect of correlating the preferred sites of mammalian fauna's burrows in the arid and semi-arid regions with the breeding sites of desert locusts is the scope for future study.

Conclusion

In this study, we have retrieved the preferential soil conditions at the surface and subsurface levels for desert locust egg-laying sites by harnessing the openly available geospatial data. The studied parameters include the percentage of sand-silt-clay content, soil texture, soil moisture, and land surface temperature. Towards this, 4116 desert locusts' egg-laying sites were retrieved from FAO's Locust Hub database for 2017-2021. The potential of open access SoilGrid ver. 2.0 data from the WoSIS database facilitated by ISRIC and SMAP L4 data products from NSIDC have been harnessed to understand the optimal range of the preferential factors that favor desert locusts for egg-laying. Threshold ranges of sand-silt-clay content and soil moisture at surface and subsurface levels reported in this research benefit for habitat modeling and detecting breeding sites. Soil texture classes that can facilitate the oviposition of female desert locusts were identified through this research. Using threshold values of various soil parameters and soil texture classes mentioned in this research will help in the early identification of breeding grounds during desert locusts' invasion period and strengthen the control operations that can aid in preventing the egg-development.

Author contributions

GD conceived and designed the experiment and also drafted the original manuscript. RH, KG, and DK have performed the analysis and tabulated the observations. RF has modeled the percentage of sand-silt-clay into USDA soil texture classes using the R programing platform. RF and AS have done the field work and contributed to the analysis. AKB and SKS have supervised, reviewed, and facilitated the necessary infrastructure for this research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

Locations details of all the desert locusts' egg-laying sites are available in FAO's Locust Hub database available at the web portal https://locust-hub-hqfao.hub.arcgis.com/. SoilGrids 2.0 are available from WoSIS database maintained by ISRIC and can be downloaded in Virtual Raster Tile (VRT) format from the web-portal (https://files.isric.org/soilgrids/latest/). Soil moisture and land surface temperature are available from SMAP L4 data products maintained by NSIDC and can be downloaded from (https://nsidc.org/data/SPL4SMGP).

Acknowledgements

The authors thank NSIDC, ISRIC, and FAO's Locust team for providing open-access to various data products used in this research. The authors would like to express sincere gratitude to all the members of ISRO's 'Standing Committee for Locust Surveillance, Alerts, and Monitoring' and staff members of Regional Remote Sensing Centre NRSC/ISRO, Jodhpur. The authors would like to express special gratitude to the officials of the Locust Warning Organisation, Jodhpur, India, for providing field-level information in connection with desert locusts. Foremost, the authors are indebted to Director, National Remote Sensing Centre, ISRO, Hyderabad, India, and express sincere gratitude for encouraging the research activities and providing the necessary infrastructure needed for this research.

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Supplementary Materials

Fig. S1 Locations of desert locusts' egg-laying sites (2017-2021) retrieved from Locust Hub web site maintained by FAO under Locust Watch program.

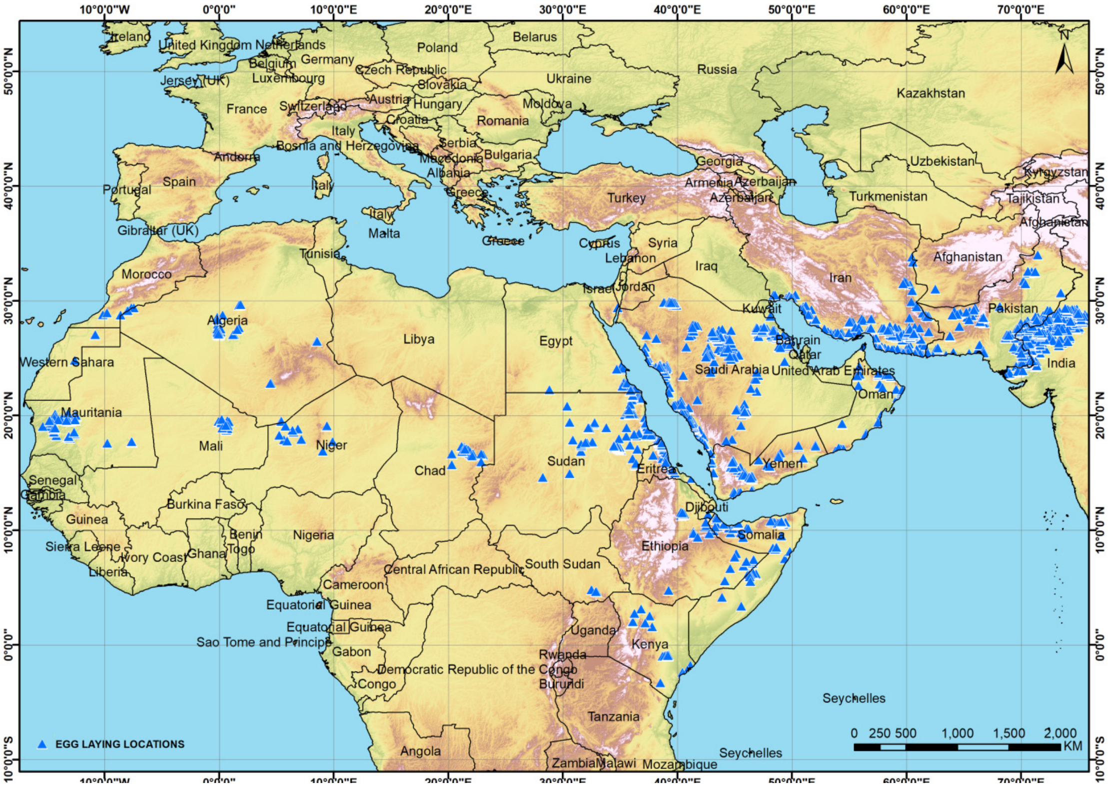

Fig. S2 Map showing a subset of global soil map of sand constituent at 0-5 cm from SoilGrids ver. 2.0 data for the extent of desert locust invasion area.