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Article

# Trends of Cochineal (*Dactylopius coccus*) Infestation as Affected by Armed Conflict and Intervention Mechanisms for Sustainable Management in Tigray, Northern Ethiopia

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**Abstract:** The cactus pear (*Opuntia ficus-indica*) is a crucial plant in Tigray, northern Ethiopia, widely distributed in arid and semi-arid environments. It serves as a seasonal food, livestock feed, fence, soil conservation, and environmental protection. Recently, the cactus pear population in Tigray have been damaged by an exotic insect, cochineal (*Dactylopius coccus*). It damaged the cactus pear populations in the region's southern, south eastern and eastern zones. The Tigray war that broke out in November 2021 exacerbated *D. coccus* infestation. A study was conducted to assess the impact of the armed conflict on the trends of *D. coccus* infestation and forward management approaches for sustainable cactus pear production in post-war Tigray. The study was conducted in the eastern zone of Tigray. Primary and secondary data were collected. The study revealed that *D. coccus* infestation increased during and post-war compared to the pre-war. The number of districts and level of *D. coccus* infestation on cactus pear populations increased. The rapid *D. coccus* spread is attributed to the impact of the armed conflict which halted the pest management practices. Different management approaches are recommended to manage *D. coccus* dissemination and sustainably produce cactus pear in the region, including pest prevention, suppression, or eradication.

**Keywords:** cactus pear; cochineal; Tigray war; management approaches

## 1. Background

The cactus pear (*Opuntia ficus-indica* L. Mill) also known as the prickly pear is believed to have originated in central and southern Mexico [1]. It belongs to the dicotyledonous plant family *Cactaceae*. This plant grows in a wide range of environmental conditions mainly widely distributed in arid and semi-arid environments and remains green even during the dry season making it particularly to grow in water scarce areas [2–4].

Cactus pear provides multiple economic, social, medicinal, and environmental benefits [4]. It serves as a food source for human, livestock feed, income generation, live fence, soil conservation, and environment protection [1,3–8].

Cactus pear (locally known as “Beles” or “ Qulqual Bahri”) is believed to have been introduced to Ethiopia in the northeast of Tigray as early as 1848 [1,9,10]. It is widely distributed in the arid and semi-arid parts of Tigray [3]. Since its introduction to the region, interest in cactus pear production has grown significantly due to its drought resistance, high biomass yield, high palatability, and tolerance to salinity [3]. In Tigray, cactus pear covers an approximately 379,338 ha, accounting for 7.4% of the total land area of the region [11]. It is among the valuable crops in Tigray serving as a seasonal food source mainly during summer months (June to September), a year-round feed for livestock, serving as a live fence, a means for soil conservation, and environment protection [12]. Nearly all rural communities in the southern, south eastern, eastern, and some parts of central zones of Tigray use the cactus pear fruit as a stable food during the summer [3,8,12]. Given the severe shortage of livestock feed sources in this area, cactus pear is utilized year-round either as a sole or in combination with other feed sources [5,13]. The cactus pear has become an integral part of the culture and economy of Tigray with its uses extending in many ways [1–6,8]. Considering the importance of the plant to the livelihood of the community, [14] described the cactus pear in the region as *a miracle plant, dromedary of the vegetation world, and the bank of life*.

Moreover, as the impact of climate change increases, cactus pear cultivation may assume greater agricultural importance in dry areas since a significant part of the land is destined to become arid and semi-arid [3,4]. It is an environmentally valuable plant, particularly suited for arid and semi-arid regions, where it aids in environmental protection, soil enrichment, carbon sequestration, and climate resilience [15]. The cactus pear’s Crassulacean Acid Metabolism (CAM) photosynthesis efficiently absorbs CO<sub>2</sub>, making it a reliable carbon sink with high water efficiency compared to C<sub>3</sub> and C<sub>4</sub> pathways, which is ideal for arid environments [16]. Its drought tolerance further strengthens ecosystem pliability, offering a habitat for various species and promoting ecosystem stability [4]. Overall, cactus pear plays a critical role in land restoration, biodiversity support, and sustainable climate adaptation.

Despite its multi-purpose livelihood benefits, the cactus pear is underutilized in Tigray [3–5], [12]. Besides, the cactus pear industry in the region faces numerous constraints that limit its growth and potential. Some of the factors include lack of improved agronomic practices, pests, inadequate research, and extension support, low absorption of modern technologies, limited linkages among value chain actors, absence of developed collection and marketing centers, and improper harvesting and post-harvest handling (poor packaging, sorting, and processing) (Berhe et al. 2020).

The productivity of the cactus pear in the region have recently been severely affected by an invasive exotic insect, the cochineal (*Dactylopius coccus* Costa), which was deliberately introduced in 2004 for the production of carminic acid [1], [3], [12]. In 2004, the insect was allowed to multiply in an open field at three inoculation sites: Endayesus in Mekelle, Tsehafti in Wajarat, and Embachera in Mehoni . These sites served as experimental release points for cultivating cochineal for export purpose. Since its release, the insect has been unattended and inadequately managed and the project failed to meet its intended goal of exporting dried cochineal. As a result, the insect spread uncontrollably, causing extensive damage to cactus pear population. By 2015, it had infested 16000 ha of both wild populations and private plantations [11]. By 2020, the figure had risen to 91,000 ha [12]. The rapid spread of pest has been facilitated by favorable climatic conditions (extended dry

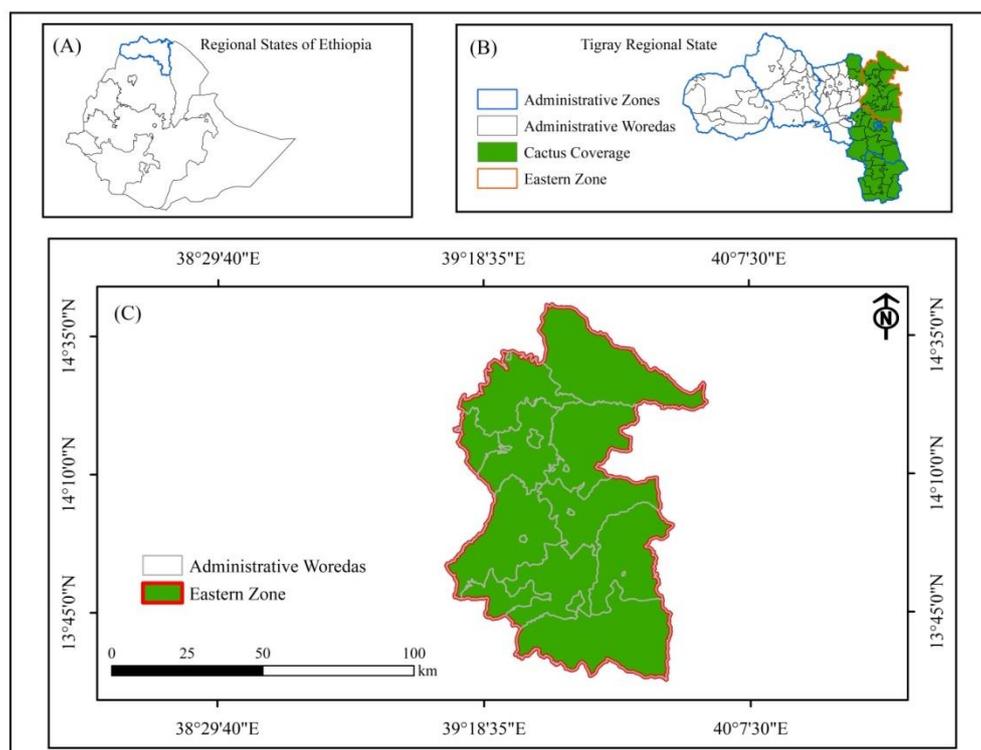
period), an abundance of cactus pear vegetation, a rapid reproduction rate, and the absence of natural enemies to keep its population below economic threshold. Moreover, the lack of a local quarantine system and ineffective pest management practices have exacerbated the situation and escalated at an alarming rate. In the region's southern, south eastern and partly eastern zones, the *D. coccus* has caused a total collapse of cactus pear production, depriving farmers of both fruits and livestock feeds. Soil degradation due to erosion has become common in areas where the pest has destroyed cactus pear.

Moreover, the armed conflict (also called the Tigray War) that broke out in November 2021 affected the agriculture sector, which resulted in the collapse of the whole system including the *D. coccus* management. For instance, as a result of the Tigray war, 81% of households lost their crops; 75% lost livestock and 94% reported agricultural components looted or destroyed [17]. Moreover, the armed conflict interrupted ecosystem restoration and increased desertification risk. For instance, the woody vegetation cover declined from 17 to 12% in less than two years (2021-2022) [18]. Similarly, *D. coccus* management in the region was left unattended during the war. The management system related to cactus pear protection and conservation collapsed as a result of the armed conflict. As the armed conflict caused huge damage to the agriculture sector of the region, it is imperative to investigate the effect of the conflict on the spread of *D. coccus* and devise coping mechanisms to contain the spread of the insect and rehabilitate cactus pear populations in the region. Therefore, this study aims to assess the trends of *D. coccus* dissemination before, during, and after the Tigray war and identify strategies to prevent the spread to new areas and contain the insect pest below the economic threshold. Specifically, the study will focus on (1) assessing the trend of *D. coccus* infestation in Tigray, (2) evaluating the impact of the Tigray war on the spread of *D. coccus*, and (3) developing sustainable *D. coccus* management options to ensure better cactus pear production in Tigray.

## 2. Methodology

### 2.1. Description of the Study Area

Before the outbreak of the Tigray war, a buffer zone had been delineated in the eastern zone to prevent *D. coccus* spread to uninfested areas. The southern and south eastern zones were already fully infested before the armed conflict. Thus, the study focuses on the status of *D. coccus* spread after the armed conflict in the eastern zone of Tigray, northern Ethiopia, compared with the status of infestation prior to the conflict (Figure 1). Though the major emphasis of the study is on the eastern zone, data on the trends of *D. coccus* dissemination in the south and south eastern Tigray prior to the conflict was also considered in the study. The eastern zone encompasses 18 woredas and 168 districts (locally called "Kebeles"). The eastern zone lies between 13°33' N latitude and 39°11' E to 39°59' E longitude [19]. Rainfall in the eastern zone has a bimodal season, in which the long rain season starts from the end of June to the beginning of September and short and sporadic rain season stays from January to March. The eastern zone is rich in its naturalized and cultivated cactus pear populations. It receives a mean annual rainfall between 520 to 680 mm and a mean annual temperature from 16 to 20 °C [19]. The zone is one of the potential cactus pear-producing zones in Tigray. The smallholder farmers in the region utilize the cactus pear predominantly for seasonal food, livestock feed, live fences, soil conservation, and environmental protection.



**Figure 1.** Study area; A) Ethiopia's regional states, B) Tigray Regional State, and C) eastern zone.

## 2.2. Method of Data Collection

Primary and secondary data were collected from the selected study areas. The primary data was gathered from key cactus pear-producing districts in the eastern zone of Tigray to determine the current occurrence, damage levels, and area coverage of *D. coccus*-infested cactus pear populations. This involved collecting data from 18 woredas (sub-zones) and 168 districts through direct field observations, interviews with agricultural experts from each district, participatory rural appraisal (PRA), and the use of ArcGIS for mapping. Field observation was conducted to document cochineal expansion, the status of cactus pear, and any disruptions or adaptive strategies in place. The PRA included the participation of two crop protection experts per woreda and five representative farmers from each district to provide information about their indigenous knowledge or practices employed for *D. coccus* management in their districts. The ArcGIS was used to map the potential shifts in cactus pear area coverage as affected by *D. coccus* spread. The secondary data were also collected from a literature review of reports from each woreda's agriculture bureau and the agricultural production records on changes before, during, and after the conflict period. Combining these methods provided a well-rounded understanding of the impacts of the armed conflict and facilitated the development of sustainable management strategies. Combining these methods provided a well-rounded knowledge of the impacts of the armed conflict and facilitated the development of sustainable management strategies.

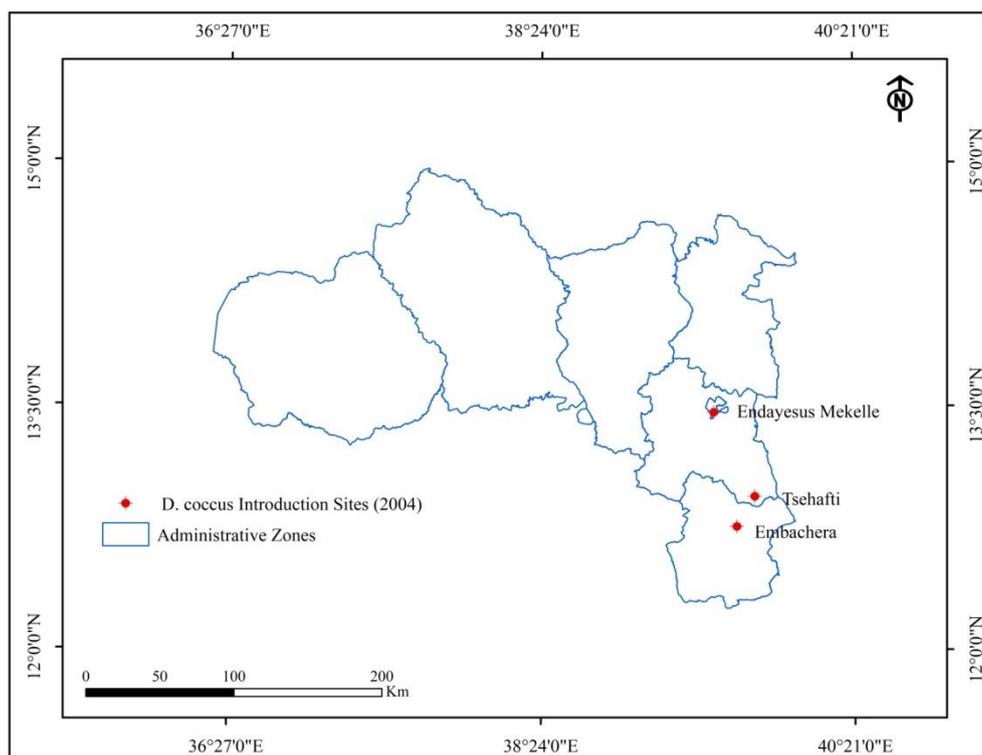
## 2.3. Data Analysis

Collected data on the number of *D. coccus*-affected districts, level of infestation, and *D. coccus*-infested cactus pear area coverage from each district before and after the armed conflict were subjected to trend analysis using Microsoft Excel and ArcGIS.

### 3. Results and Discussion

#### 3.1. Trends of *D. coccus* Dissemination in Tigray Before the Conflict

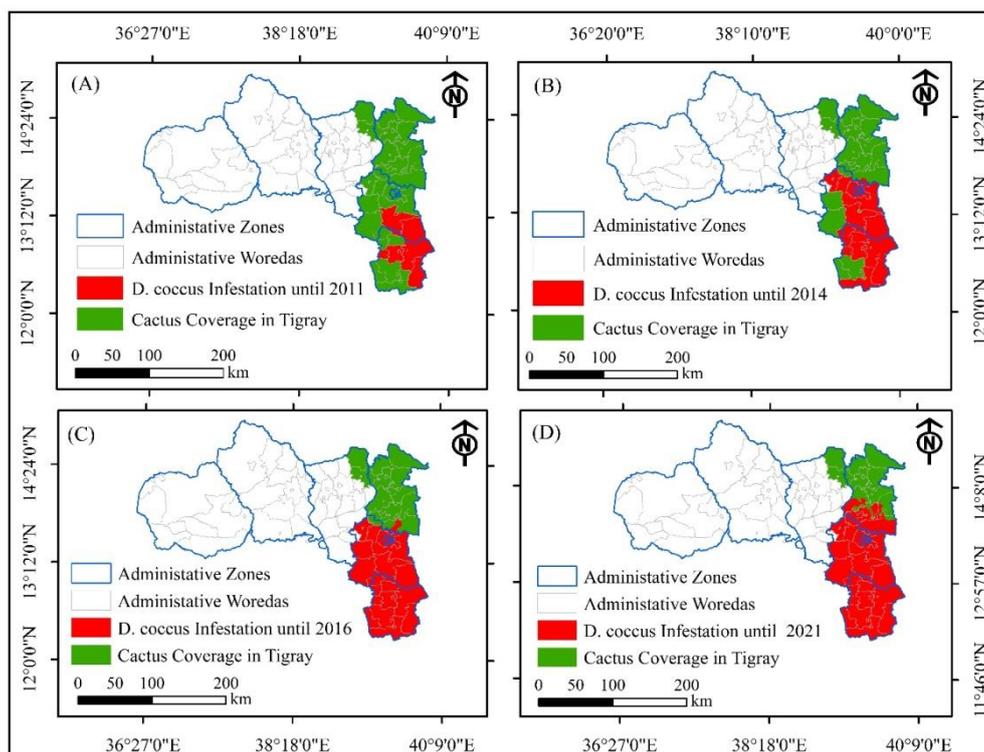
*D. coccus* was initially introduced in three sites namely Endayesus (Mekelle zone), Tsehafti (south eastern zone), and Embachera (southern zone) in 2004 (Figure 2). From the first introduction to 2010, the spread to new districts had been slow.



**Figure 2.** *D. coccus* introduction sites in 2004.

As depicted in Figure 3, *D. coccus* infested a few districts in the south and south eastern zones since inoculation till 2011. However, the level of *D. coccus* dissemination has increased rapidly since 2011. From 2011 to 2014, it was disseminated to the majority of cactus pear-producing areas of south and south eastern woredas except for Ofla and Sahartisamre (Figure 3, *D. coccus* infestation until 2011, *D. coccus* infestation until 2014). *D. coccus* infestation was also observed in 2014 in Kiltawlaelo woreda of the eastern zone but immediately controlled without causing economic damage on cactus pear populations (Figure 3B). The insect expanded to all cactus pear-producing areas of the south and south eastern zones of Tigray in 2016 (Figure 3C). Before the war erupted in November 2021, the *D. coccus* infestation had fully devastated the cactus pear plants in southern and south eastern zones of Tigray (Figure 3D).

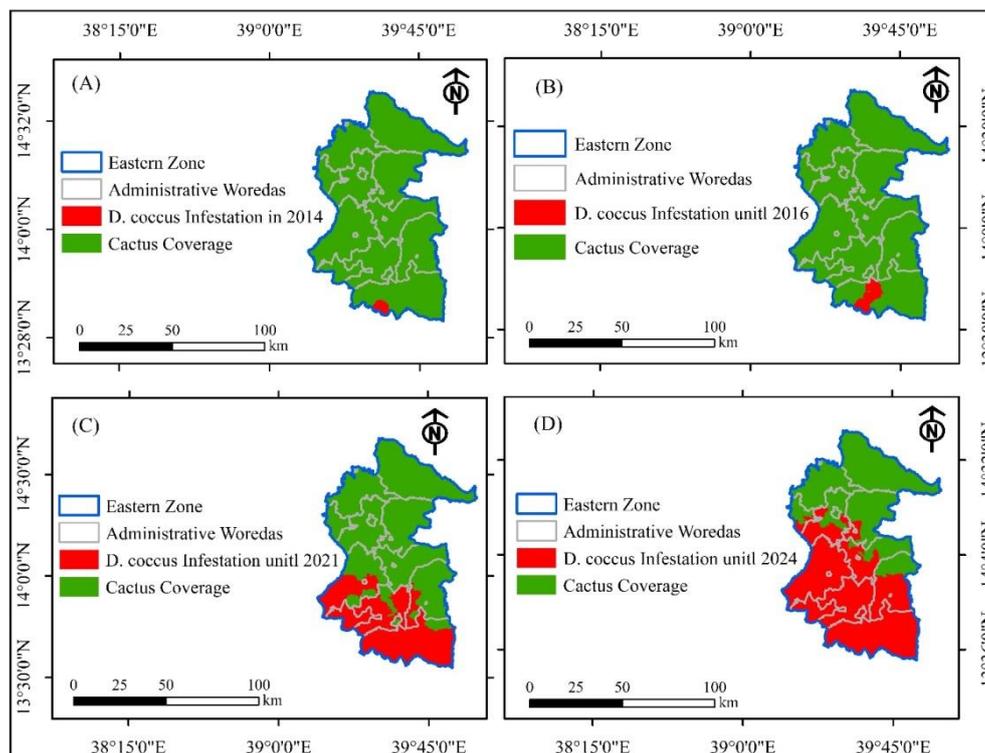
The insect infestation in eastern zone districts was kept minimal until 2021 by integrating cultural, mechanical, public campaigns to clean infested fields, and chemical methods of pest management. The infestation level in the eastern zone of Tigray was limited to six woredas and affected limited cactus pear plants (2676.35 ha i.e. 5.7% of the total cactus pear area coverage) until November 2021 (Figures 3D and 4C, Table 1).



**Figure 3.** Pre-war *D. coccus* spread in cactus pear-producing areas in Tigray. *D. coccus* infestation until 2011 (A); *D. coccus* infestation until 2014 (B); *D. coccus* infestation until 2016 (C); *D. coccus* infestation until 2021 (D).

**Table 1.** Trends of *D. coccus* spread in terms of the number of districts and the areas (hectares) infested in the eastern zone of Tigray (November 2021 – May 2024).

Name of Woredas	Number of districts	Cactus pear area coverage (ha)	<i>D. coccus</i> affected districts			<i>D. coccus</i> -infested cactus pear coverage (ha)		
			before the war (until Nov. 2021)	until May 2023	until May 2024	before the war (until Nov. 2021)	Nov 2021 - May 2023	May 2021 - May 2024
Tsiraewenberta	12	1353.10	10	11	11	215.75	362.00	414.75
Agulae town	3	6.50	1	3	3	1.00	6.50	6.50
Kilte awlaelo	13	2060.99	11	13	13	87.76	794.61	1806.60
Wukro town	3	4.67	1	2	3	1.50	4.67	4.67
Geralta	8	2342.00	8	8	8	2342.00	2342.00	2342.00
Atsbi town	3	3.00	0	0	0	0.00	0.00	0.00
Atsbi Geter	12	2549.20	3	3	8	2.25	1.75	22.14
Hawzien	23	3580.25	8	15	21	27.59	131.26	607.63
Hawzen town	4	6.50	1	4	4	1.47	6.50	6.50
Freweyni town	4	7.00	0	0	0	0.00	0.00	0.00
Saesie-tsaedaemba	12	4109.25	0	2	8	0.00	2.00	27.59
Edaga-hamus town	4	5.00	0	0	0	0.00	0.00	0.00
Sibuha saesie	14	8321.00	0	0	2	0.00	0.00	0.80
Gantaafeshum	17	4151.50	0	2	9	0.00	0.00	5.59
Gulemekeda	15	4173.25	0	0	0	0.00	0.00	0.00
Bizet	7	664.63	0	0	2	0.00	0.00	1.20
Irob	7	14953.50	0	0	0	0.00	0.00	0.00
Adigrat	7	75.00	0	0	0	0.00	0.00	0.00
<b>Total</b>	<b>168</b>	<b>48366.34</b>	<b>43</b>	<b>63</b>	<b>92</b>	<b>2676.35</b>	<b>3644.79</b>	<b>5239.47</b>



**Figure 4.** *D. coccus* expansion in the eastern zone of Tigray. A) *D. coccus* infestation reported in 2014, B) *D. coccus* infestation reported in 2016, C) *D. coccus* infestation reported in 2021, and D) *D. coccus* infestation reported in 2024.

### 3.2. Trends of *D. coccus* Dissemination in the Eastern Zone of Tigray Before the Armed Conflict

The first infestation was detected on cactus pear plants in the eastern zone in 2014 in Kilteawlaelo Woreda (Figure 4A). Until 2016, the level of infestation was low, limited to a few districts in Kilteawlaelo Woreda (Figure 4B). Until November 2021, *D. coccus* was detected in only 43 districts out of 168 villages of the eastern zone of Tigray, infested an estimated 2676.35 ha of cactus pear population (Figure 4C). This accounted for 5.7% of the total cactus pear area coverage in the region (Figure 4C, Table 1) in areas near to south eastern zone. The infestation of *D. coccus* was recorded in four out of the eighteen woredas, namely, Gerealta, Tsiraewomberta, Kilteawlaelo, and Hawzien. The *D. coccus* was recorded in eight out of eight, ten out of twelve, eleven out of thirteen, and eight out of twenty three districts in Gerealta, Tsiraewomberta, Kilteawlaelo, and Hawzien, respectively. This result shows most of the districts in the four woredas were affected by *D. coccus* (Table 1).

In terms of infestation level, the highest infested cactus pear population was observed in Gerealta (2342 ha) followed by Tsiraewomberta (217.75 ha), Kilteawlaelo (87.76 ha), and Hawzien (27.59 ha) (Table 1). The infested cactus pear population of these woredas accounts for 99 % of the total area infested in the eastern zone of Tigray. As a result, the buffer zone had been delineated in eastern zone districts proximate to the South eastern zone covering parts of Gerealta, Kilteawlaelo, and Atsbiwenberta. The districts north of the buffer zone were expected to be free of insects with integrated management approaches such as cultural, mechanical, public campaigns to clean infested fields, and chemical methods of pest management [3].

### 3.3. The Effect of the Armed Conflict on the Management of *D. coccus*

#### 3.3.1. The Neglected *D. coccus* Management Practices

From 2016 to 2021, prior to the outbreak of the war, the spread of *D. coccus* was confined to a few woredas (Figures 3 and 4) and infestation levels were kept minimal through the implementation

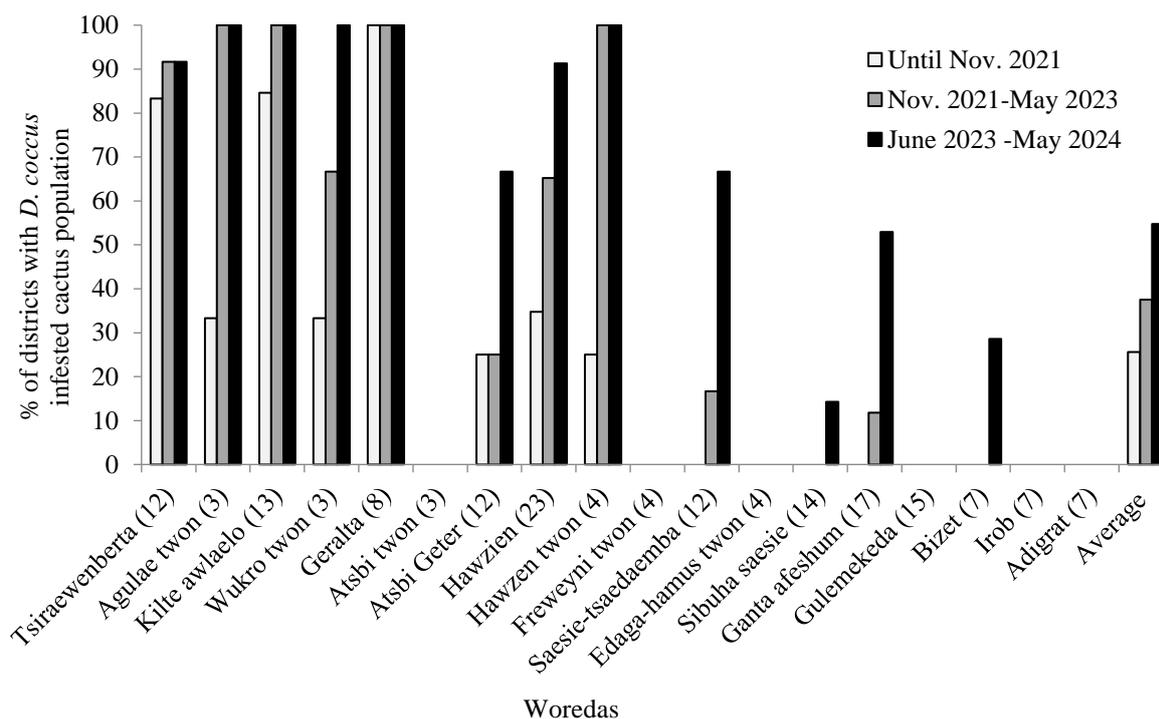
of various management practices. The management strategies focused on short-term preventative methods to limit the spread of the insect pest to uninfested areas and a medium to long-term plan by devising control methods for insect containment or eradication. The preventative methods involved integrated cultural management practices such as scouting, demarcated buffer zones between the infested and uninfested areas, awareness creation to producers and agricultural experts, mechanical methods such as cutting and burying *D. coccus*-infested cladodes or the whole plant which showed signs of cochineal infestation, burning and burying cochineal infested cladodes or the whole plant, botanicals, and insecticides [3,20]. In addition, limiting the movement of livestock and humans from infested to non-infested areas was partially implemented. The application and integration of the various management methods reduced the spread of the pest before the war.

The scout experts at the buffer zone played a significant role in mobilizing the community, scouting, and preventing *D. coccus* from spreading [3]. As a result, from 2018 to 2021, the *D. coccus* infestation in new areas was insignificant and limited to the infested areas. However, after the war erupted in November 2021, all the systems of *D. coccus* management in the region collapsed. The scout experts employed to supervise the management practices in the buffer zone lost their jobs. The pest management networks from the regional level to the Kebele level for *D. coccus* management collapsed. As a result, *D. coccus* rapidly disseminated to other districts beyond the buffer zone within the two years of armed conflict and even post-conflict.

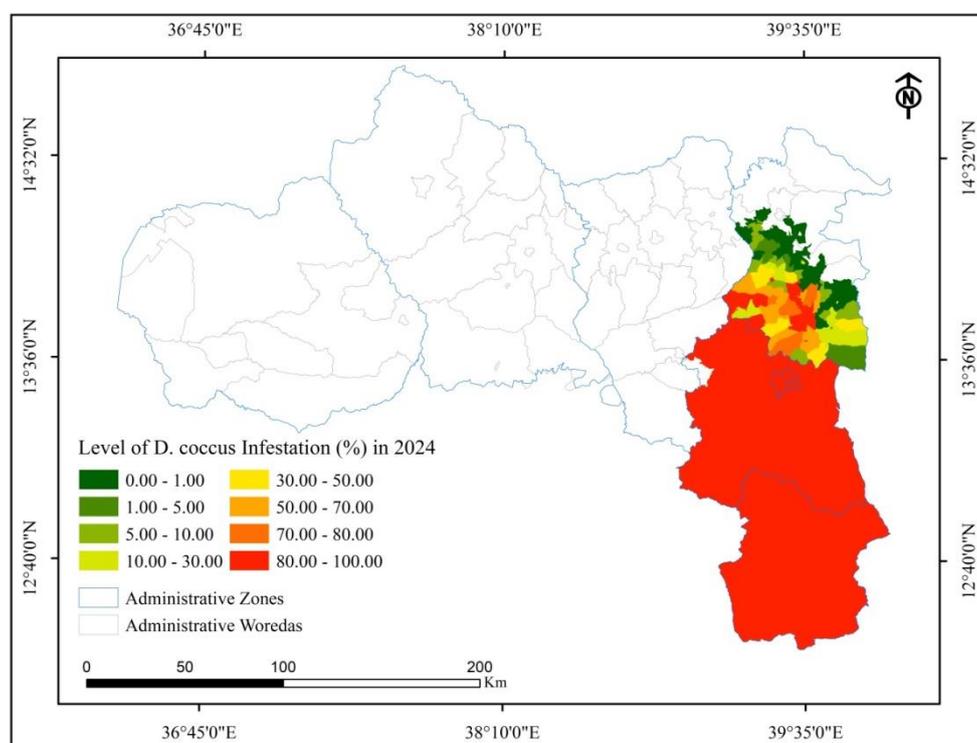
### 3.3.2. Trends of *D. coccus* Infestation as Affected by the Armed Conflict

As a result of the conflict, the agricultural system of the region was devastated and the same holds true for the *D. coccus* management practices. The armed conflict resulted in widespread *D. coccus* infestation in the cactus pear population. Insect-free cactus pear populations before the war became prone to *D. coccus* infestation. From November 2021 to October 2023, *D. coccus* infested cactus pear populations in ten out of 18 Woredas of the eastern zone of Tigray (Figure 4D and Table 1). The number of districts with *D. coccus*-infested cactus pear populations increased dramatically (Table 1, Figure 5). The total number of districts in the eastern zone with *D. coccus*-infested cactus pear populations increased from 43 (25.6%) in October 2021 to 63 (or 37.5%) in May 2023, and 92 (54.8%) in May 2024 out of 168 districts (Figure 5). *D. coccus* infestation was detected in all districts of Agulae town, Kilteawelaelo, Wukro town, Gerealta, and Hawzien town (Figure 5) during and post-conflict. By September 2024, *D. coccus* was detected in Gantaafeshum, Bizet, Sibuhasaesie, and Gulemekda with no or little impact on cactus pear populations. On the other hand, Irob, Adigrat, Freweyni town, Edagahamus town, and Atsbi town were free of any *D. coccus* occurrence so far.

In area coverage, a total of 2676.35 ha of cactus pear populations were infested by *D. coccus* till November 2021. The level of infestation rose to 3644.79 ha (26.57% increase) in May 2023 and 5239.47 ha (48.92% increase) in May 2024 (Table 1). However, the percentage of *D. coccus* infestation varied among the woredas (Table 1, Figures 5 and 6). Till May 2024, from the woredas which had been already affected by cochineal before the war, the highest increase rate in cochineal infestation on cactus pear populations was observed in Kilteawelaelo (87.67%) of the total cactus pear coverage infested, followed by Tsiraewenberta (30.65%) of the total cactus pear coverage infested (Figure 6). During the war and post-war periods, the insect was disseminated to other woredas of the eastern zone involving Saesie-tsaedaemba, Sewhasaesi, Gantaafeshum, and Bizet (Figure 6). The cactus pear population in three towns namely Hawzien, Wukro and Agulae were also infested by *D. coccus*. As depicted in Figure 6, the level of *D. coccus* infestation and the number of districts affected increased in September 2024 compared to November 2021. The alarming dissemination rate of *D. coccus* during and post-conflict is attributed to the collapse of the management approaches. There is poor intervention in *D. coccus* management which is threatening the cactus pear production of the remaining insect-free districts of the eastern zone.



**Figure 5.** Percent of districts with *D. coccus*-infested cactus pear populations. Numbers in parenthesis indicates the number of districts.



**Figure 6.** The heat map that shows the level of *D. coccus* infestation in the eastern zone in May 2024.

#### 4. Existing Challenges on the Management of *D. coccus*

The *D. coccus* is spreading to new cactus pear population districts because of the existing challenges in dealing with the problem. The major challenge arises from the lack of scout deployment and public campaigns to halt the spread of the insect pest to new districts. There has been little intervention to prevent the spread or control of *D. coccus* since the eruption of the armed conflict and even after the Pretoria Agreement (peace treaty between the government of Ethiopia and the Tigray People's Liberation Front (TPLF) that was signed on 2 November 2022). Another challenge arises from the fast dissemination nature of the insect pest. *D. coccus* is mainly disseminated by wind and phoresis and high during the dry and windy season. If preventative methods are not applied, the infestation rate is expected to rise, leading to devastating damage to the remaining cactus pear population in the region. There is a lack of integrated approaches in management methods, human resources, and experts to provide a ground-breaking solution to the problem. The lack of a buffer zone to prevent *D. coccus* dissemination is another challenge that favors fast dissemination of *D. coccus* to the free districts if intervention is not applied as fast as possible. Poor research and development in *D. coccus* management, cactus pear rehabilitation, and planting techniques are also contributing factors. Another challenge is the existing unmanageable planting nature of the cactus pear population. The wild and cultivated populations characterized by overgrowth and lack of spacing among cactus pear plants make *D. coccus* management challenging to apply pest management practices such as pesticides. Moreover, there is no clarity on whether or not harvesting and commercializing *D. coccus* for carminic acid production is to be considered as a means of control from dissemination to new districts. The most critical point here is reaching clarity among leaders, experts, institutes, and the community through an in-depth analysis of whether legalizing *D. coccus* multiplication and harvesting is a blessing or curse. An expert-wise decision on whether harvesting *D. coccus* should be considered as part of the cochineal management to create a better environment is important.

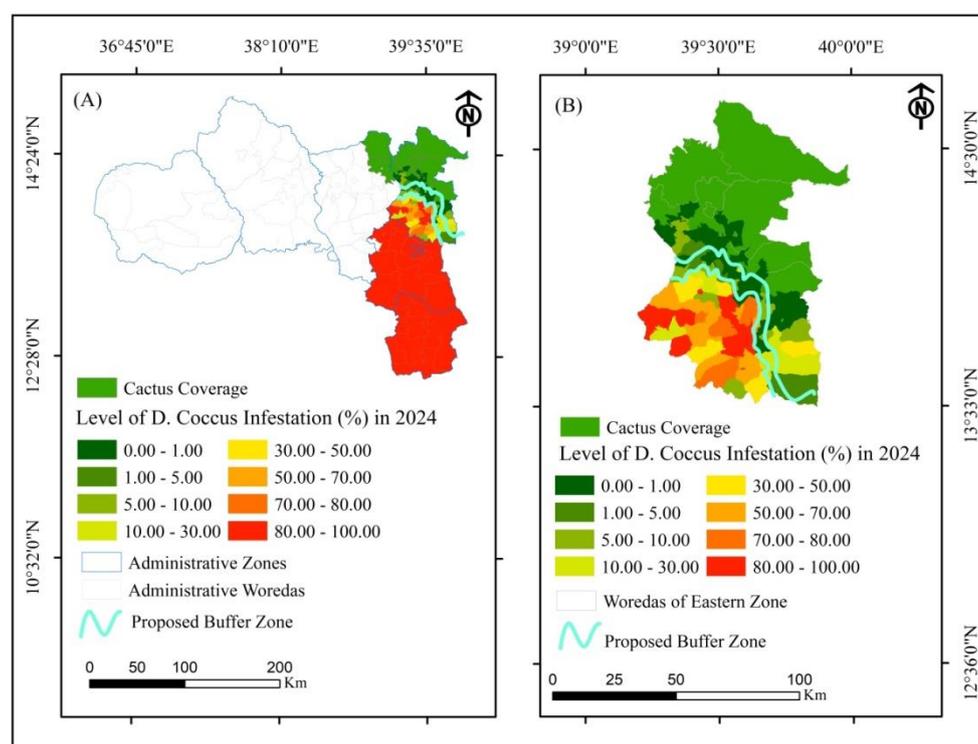
#### 5. Way Forward for Integrated *D. coccus* Management to Restore and Sustainably Produce Cactus Pear in Tigray

*D. coccus* has become one of the invasive insect pests with damage to vast areas of neutralized and cultivated cactus pear populations in Tigray. The dissemination of the insect is at an alarming rate that demands action and the development of integrated *D. coccus* management. Given the nature of the cactus pear population in the region and the fast dissemination of the insect pest as depicted in this study, it is paramount to forward the approaches for integrated *D. coccus* management and sustainable production of cactus pear in Tigray. The proposed management approaches are intentionally incorporated in this study to contribute to making informed decisions for the *D. coccus* management and sustainable cactus pear production in the region.

##### 5.1. Preventative Approach

In saving the remaining cactus pear population in Tigray, the first step in *D. coccus* management is expected to focus on preventative methods to halt the dissemination of the insect pest to uninfested districts. Before the armed conflict preventative methods involved delineating a buffer zone, scouting, cutting, and burying cladodes with the sign of immature cochineal, burning, cutting, and burying cladodes with the sign of immature cochineal (nymph) [3]. Besides, quarantine, fruit packing material hygiene, and limiting movement of livestock and humans from infested to non-infested districts had been part of the preventative methods. The preventative approach can be effective if the smallholder farmers who own cactus pear populations are involved, technically and financially supported, public campaigns to clean infested fields are arranged, and awareness is offered. Above all, delineating a buffer zone could be a priority to halt the overwhelming dissemination of the insect pest to other cactus pear-producing districts of the zone. While delimiting the buffer zone, it is paramount to consider the infestation levels of districts. In terms *D. coccus*-infested cactus pear population areas coverage, some of the Woredas such as Saesietsaemba, Sibuhasaesie, and

Gantafeshum show low levels of infestation while Woredas such as Kilteawlaelo, Atsbi Geter, Hawzien and Tsiraewonberta have shown high infestation. The *D. coccus* in the woredas with low infestation levels can be controlled by applying cultural, mechanical, and chemical methods. With the assumption that these woredas are expected to be free or with low cochineal infestation levels below the economic threshold, the buffer zone can be demarcated within a 5 Km buffer zone between infested districts and non- (less)-infested districts in the eastern zone of Tigray as proposed in Figure 7. Based on this, towards the north of the buffer zone, integrated preventative approaches are applied to halt the dissemination of *D. coccus* to other districts whereas, to the south of the buffer zone, suppression strategies have to be developed for the already infested districts based on the level of infestation to reduce the pest population to the below economic threshold.



**Figure 7.** Proposed buffer zone to prevent the spread of *D. coccus*. A) Map of Tigray region with buffer zone delineation; B) Map of eastern zone of Tigray with buffer zone delineation.

### 5.2. Pest Suppression Approach

Apart from the preventative approach, in districts where *D. coccus* is causing economic loss, it is recommended to apply management mechanisms that reduce the *D. coccus* population to the below economic threshold and rehabilitating the cactus pear population in the affected districts of the region is vital. The management approaches are expected to integrate various control methods of *D. coccus*. The following management methods in a single or integrated approach are recommended to reduce or control *D. coccus*.

*Awareness creation and public campaigns:* There is a poor understanding level and awareness about the biology of *D. coccus* and its management methods at different leadership levels and in the community in Tigray. The same holds about the economic opportunities and drawbacks of the *D. coccus* introduction to the region. Therefore, awareness creation and training on the threats and opportunities of cochineal and its impact on cactus pear is crucial. Without public campaigns and coordinated effort of the small-holder farmers who own the cactus pear, experts, community leaders, local and international NGOs, and government, it is difficult to halt the fast dissemination of the

insect. As part of *D. coccus* management approaches, it is imperative to mobilize small-holder farmers and collaborate with stakeholders at different levels. Before the war, awareness creation and public campaigns had been parts of the integrated *D. coccus* management in the region [3].

*Mechanical methods:* Removing the *D. coccus*-infested cactus pear population using different techniques can be considered as one control method. This may involve cutting, burning, and burying infested cladodes or the whole plant based on the level of infestation. Reports show that mechanical methods had been employed to prevent the dissemination of *D. coccus* in Tigray before the armed conflict [1,3,21].

*Chemical control:* A plethora of findings show that insecticides and insecticidal soaps are effective in killing different life stages of various species of cochineal insects [7], [22–24]. However, the absence of proper spacing between and among the cactus pear population in Tigray is a challenge for applying chemical insecticides. If the cactus pear population is managed to have appropriate spacing and access, chemical insecticides can be effective in controlling *D. coccus*.

*Harvesting and commercializing *D. coccus* for carminic acid production:* After cochineal was introduced to Tigray in 2004, it was not harvested on time for commercial use [4]. There are plenty of experiences for utilizing both cactus and cochineal with due consideration that protected management is required for *D. coccus* harvesting and multiplication. Reports show that that the cochineal insect harvest would have increased from 3,025 in 2011 to 60,253 tons of dye in 2018. Out of this pool of dye harvests, \$24012200 would have been obtained from the carminic acid [4]. Because of this, the cochineal introduction to Tigray is considered as a missed opportunity in a region of huge cactus populations [4], [6]. Therefore, as part of *D. coccus* management and utilization approach, commercializing cochineal for the production of carminic acid should not be ignored from the list of management options. It is time to think of changing the challenges and wasted fortune to plenty of opportunities through which the region can economically gain by exploiting both the cactus pear and *D. coccus*. The region should bring this issue as a point of discussion among different actors in the sector and make an in-depth analysis of management strategies, change in perception, create awareness of the community about *D. coccus* commercializing, and possibilities of exploiting cactus pear and the insect to gain economic benefit. Thus, the region is expected to consider exploiting *D. coccus* for economic purposes in a scientifically proven and protected manner as an option to reduce the pest population in the already devastated districts of the region. The potential cactus-producing zones can be clustered according to the availability of the insects. One option is allowing the harvesting of *D. coccus* in zones with high infestation levels while preventing the dissemination of the insect to the free districts and incentivizing farmers in the free districts to modernize their cactus pear production and create market linkage. Another alternative is allowing investment in *D. coccus* multiplication in a protected structure such as a Greenhouse while preventing open-field multiplication. Farmers in the free districts will be linked to the firms by allowing them to supply cladodes for *D. coccus* multiplication in a protected structure. Considering these and other options is paramount to make an informed decision on whether or not to commercialize cochineal for carminic acid production or to consider it as a blessing or curse.

*Selection of resistant cactus pear varieties:* Searching for local varieties or introduction of cactus pear varieties resistant to *D. coccus* is also a management option to consider containing the pest population below the economic threshold. The cactus species *Opuntia stricta* and *O. robusta* have shown high resistance to *D. coccus* in a study conducted under laboratory and field conditions [25]. The cactus pear species in Tigray is *O. ficus-indica*, characterized by varied population types. The different population types (local cultivars) in Tigray have yet to be fully tested for their resistance. In other countries, there are findings those cultivars of *O. ficus-indica* are resistant to *D. coccus*. For instance, Berhe et al (2022) found that *O. ficus-indica* cv. 'Rojo Pelon' was resistant to *D. coccus*. In another study in Tigray, *O. robusta* and *O. stricta* were found resistant to *D. coccus* [12]. Therefore, the different resistant species or cultivars can be considered as a means to suppress *D. coccus* in Tigray.

*Botanicals:* Plant extracts from plants possessing insecticidal chemicals can be considered an option for *D. coccus* containment below an economic threshold level. There are some trials on the

efficacy of botanicals on the mortality of cochineal. For instance, extracts of leaves of tree tobacco (*Nicotiana glauca*) caused high mortality of female *D. coccus* [20]. Another study also showed extracts from *Solanum linnaenum* and *Nerium oleander* caused high mortality of *D. coccus* [8]. Considering these promising findings, botanicals could be an integral part of integrated *D. coccus* management.

*Biological control:* Searching for any natural enemies in Tigray that might be adapted to *D. coccus* is imperative. Alternatively, it is important to consider introducing exotic natural enemies like beetles including *Chilocorus cacti*, *Hyperaspis trifurcate*, and the lepidopteran species like *Laetilia cocci*. Reports show that the *C. cacti* controls different cochineal species [26]. Also a research finding shows that *H. trifurcate* effectively controls cochineal [27]. Therefore, utilizing these experiences to consider biological control as a means of *D. coccus* control through either conventional, augmentative, or conservational methods is important.

*Proper agronomic practice to grow cactus pear:* To successfully implement the above control methods, emphasis on appropriate agronomic practice to grow cactus pear should be placed on establishing the new cactus populations in Tigray. The existing population in Tigray lacks proper spacing and grows in hard-to-reach places such as the top of mountains and steep slopes, and this contributes to the spread of *D. coccus* in Tigray. A spacing of one to two meters between plants and two to three meters between rows is recommended for cactus growing for fruit and vegetable (cladode) production [28]. Proper spacing ensures adequate airflow, prevents disease and pest spread, reduces interspecific competition among cactus plants, and increases yield. Moreover, adequate spacing facilitates pest management by enhancing the application of pesticides and botanicals, releasing biological controls, and monitoring the effectiveness of the applied control methods.

### 5.3. Eradication Approach

Eradication is the application of phytosanitary methods to eliminate a pest from an area or geographic region [29]. It is implemented after a careful assessment of anticipated economic, ecological, and social consequences. The eradication approach is the most challenging method to achieve due to its substantial resource requirements and difficulty to implement. However, there are few success stories of pest eradication. Few among many, Myers [30] stated screwworm (*Cochliomyia hominivorax*) through sterile insect release (SIR) program (1958-1960) in Florida and cattle tick (*Boophilus annulatus*) by exclusion, disinfection, and cattle quarantine in the USA as successful eradication programs. Whereas the Gypsy moth and medfly eradication programs tried were recorded as unsuccessful. It is understandable that the eradication approach as a stand-alone technique is difficult to achieve as it demands a multi-year support program. Sterile Insect Technique (SIT), conventional biological control, host resistance, and other techniques can be considered as options for success stories of pest eradication *D. coccus*. However, eradication of cochineal from Tigray could be very difficult given the resource limitations and high commitment it demands. In this regard, containment of cochineal below the economic threshold by employing the preventative and suppression management approach or commercializing cochineal for carminic acid production could be an alternative option instead of eradication approach.

## 6. Conclusions

Regardless of the immense livelihood functions it provides, the cactus pear is one of the underutilized plants in the region. It has been devastated by *D. coccus* in the last two decades. *D. coccus* completely damaged the cactus pear plants in the south and south eastern zones and partially disseminated to the eastern zone of Tigray before the armed conflict erupted in November 2021. Prior to the conflict, the spread of *D. coccus* to new districts in the eastern zone of Tigray had been effectively slowed through an integrated management approach and the establishment of a buffer zone between infested and free areas. The study reveals that the conflict led to the collapse of these management practices, resulting in a significant increase in pest dissemination. The rapid spread of the insect resulted in damage to significant cactus pear area coverage and disseminated to new

districts that have high cactus pear population area coverage. Considering the fast-spread nature of the insect, it is vital to apply integrated *D. coccus* management approaches including pest prevention, suppression, and eradication that could contribute to sustainable cactus pear production while changing the challenges posed by the insect to an economic opportunity by developing a strategy for protected *D. coccus* harvesting and commercialization. To restore and sustainably manage cactus pear populations, it is recommended to develop a strategy that promotes the exploitation of both the multi-purpose cactus pear and the *D. coccus* known for its carminic acid production by introducing protected and sustainable production approaches. In addition, further study about the impacts of climate change on the rapid invasion of *D. coccus* is crucial to forecast its effects with the ever-increasing global warming related issues.

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