Influence of soil moisture on mesoscale convective initiation in central Mexico

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ABSTRACT

The presence of deep moist convection in a large part of Mexico is a condition typical of summer; the effects of land surface processes and mesoscale circulations are usually not included in the diagnostic and forecasting of deep moist convection, mainly because of the scale at which they occur. This study examines the effect of the soil moisture fluxes on convective initiation in the central region of Mexico during the summer periods of 2010–2014. Other aspects considered are the function of the average flux of the boundary layer in the transport of humidity towards the initiation zone. Remote sensing satellite data used are the cloud-top temperature, soil moisture, land surface temperature and precipitation. The results show over the initiation zone an increase in the soil moisture and a decrease in the land surface temperature in the direction of the mean flux at low levels. The soil moisture anomaly (SMA) presents a temporal variability being May, the composite more similar to previous studies, initiation zone drier and warmer than surroundings. The background low-level winds have an important role in the displacement of convection core and creating different features of SMA and land surface temperature anomaly.

Introduction

Theoretical background

The study of the effects of surface fluxes on the initiation of convection that generates precipitation in the tropics represents a challenge because of the complex interchange of energy and humidity between the surface and the atmosphere (Pielke, 2001). Soil moisture controls the distribution of energy available in fluxes of latent and sensible heat, and it determines the superficial runoff through the control of evapotranspiration (Ho-Hagemann, Hagemann, & Rockel, 2015); this is related with the fluxes of energy, water and carbon (Dirmeyer, Koster, & Guo, 2006; Koster et al., 2004; Seneviratne & Stöckli, 2008).

Surface fluxes come to favour precipitation directly through the transport of humidity to the atmosphere or indirectly through the dynamics of the planetary boundary layer and the mesoscale circulations (Guillod, Orlowsky, Miralles, Teuling, & Seneviratne, 2015). Studies such as those by Pal and Eltahir (2001), Taylor et al. (2011), Taylor (2015) and Taylor, De Jeu, Guichard, Harris, and Dorigo (2012) point out the importance of the moisture fluxes from the surface in the activation of the deep convection, which in some cases give place to abundant precipitation.

The effects of soil moisture are reflected directly in the limitation of evapotranspiration, repercussing in the development of the planetary boundary layer and, hence, in the initiation and intensity of convective precipitation (Eltahir, 1998; Pal & Eltahir, 2001), the soil moisture—precipitation feedback is shown in Figure 1. A study of the effects of soil moisture on the convective initiation in Europe (Taylor, 2015) showed that the initiation of convection is favoured over regions with low soil moisture but surrounded by wetter areas. This agrees with his earlier study (Taylor et al., 2012) which showed that the rains in the Sahelian region that occur after midday are products of the heterogeneity in the soil moisture (at scales of tens of kilometres); hence, a similar process may be important in regions of dry–humid transition in the tropics. In the eastern USA and Mexico, variations in the surface fluxes lead to 10% to 20% changes in the probability of rain during summer afternoons (Findell, Gentine, Lintner, & Kerr, 2011). Hence, the effects of the soil moisture–atmosphere feedback are important in the weather and in the regional climate of various parts of the world (Froidevaux, Schlemmer, Schmidl, Langhans, & Schär, 2014).
State of the art

The precipitation generated by the local convection frequently occurs at small spatial scales (tens of kilometres), so knowing the whereabouts and time of its initiation continues to be a challenge for the forecasters (Banacos & Schultz, 2005). Study of the local convection usually requires the use of measuring instruments with high temporal and spatial resolution (e.g. RADAR) to evaluate the origin and evolution of the instability-convection-rainfall process (Jirak, Cotton, & McAnelly, 2003). These types of studies are still scarce in Mexico. However, the quantities of rain generated by the convective systems become significant; for example, Fritsch, Kane, and Chelius (1986) showed that in some regions of the USA the rain derived from the Mesoscale Convective System (MCS) can represent 30% to 70% of the summer total (taken from April to September).

In Mexico, annual precipitation is of monsoon type: a rainy season in summer, and less rain in winter (Domínguez, 2012; Franco-Díaz, 2015; Herrera, Magaña, & Caetano, 2015; Magaña, Amador, & Medina, 1999; Magaña & Caetano, 2005; Méndez & Magaña, 2010). In the central region of Mexico, the precipitation during summer increases in intensity after midday (Figure 2); hence, it is expected that much of the precipitation would be related to the activity of the planetary boundary layer, influenced directly or indirectly by the surface flows.

The soil moisture–precipitation feedback can be examined over the south-central region of Mexico (Figure 3) considering the parameters suggested by Pal and Eltahir (2001).

The components of the feedback process (Figure 4) show how the convective precipitation increases month by month, mainly from May to July. The effect of increased cloud (lower temperature) is seen in the decrease in the emission of long-wave radiation; there is also a decrease in the entry of short-wave radiation because of the cloud cover. The increase in latent heat and the decrease in superficial sensible heat are perceptible, produced by a greater quantity of soil moisture. The moist static energy increases mainly from May to June, probably through the greater influence of the specific humidity in the atmosphere; the decrease from June to September can be attributed to the influence of the decrease in temperature. Therefore, it is necessary to study the role of surface fluxes, in particular the soil moisture, in activating the deep convection during the summer in Mexico, in terms of mesoscale circulations.

Data and methods

The central region of Mexico was selected (Figure 3) because it is the transition zone of rain intensity, with the region to the south having more abundant rains than the region to the north; Hence, the selected domain represented contrasting areas of humidity and precipitation: the south is very humid, and the
north is dry. The summer contrast of precipitation is shown in Figure 2. The terrain is generally complex (Figure 3), but a topography filter was used to differentiate convection forced by orography and surface processes over level areas where local fluxes can be a determining factor in the activation of convection.

**Data**

We used remote sensing data (i.e. satellite retrieval of cloud-top temperature, soil moisture, land surface temperature, land cover type, and precipitation) to examine local convection; this took advantage of improved products derived from high-resolution satellite data. Whereas the surface wind data are ERA-Interim reanalysis (Dee et al., 2011), the topography of a model of elevation (US Geological Survey, 1996) and the water bodies are cartographic data from the Instituto Nacional de Estadística y Geografía (INEGI). In a general manner, the data for cloud-top temperature (PATMOS-x) have a temporal resolution of 1 h and spatial resolution of 0.1°, and cover the period 1995–2014 (Heidinger, Foster, Walther, & Zhao, 2014). The soil moisture data (CCI Soil Moisture ECV project) have a daily temporal resolution and a spatial resolution of 0.25°, and cover the period 1991–2014 (Liu et al., 2012, 2011; Wagner et al., 2012). The data for land surface temperature (Moderate Resolution Imaging Spectroradiometer MODIS/Terra LST/E v5) are available at a daily temporal resolution and a spatial resolution of 1 km, and the base covers from 2000 to the present (Wan, 2006). The precipitation data (CPC MORPHing technique; CMORPH) have a 3-h temporal resolution and a spatial resolution of 0.25° (Joyce, Janowiak, Arkin, & Xie, 2004). The data for land cover type (MODIS Land Cover Type) have a spatial resolution of 500 m (Friedl
In the case of the horizontal wind, the components of the $u$ and $v$ of the wind at 10 m, 18 UTC hour, were downloaded at a daily temporal resolution and a spatial resolution of 0.25°; these data are available for the period from 1979 to the present (Dee et al., 2011). The topography (Global 30-Arc-Second Elevation Data Set GTOPO30) has a spatial resolution of ~1 km (US Geological Survey, 1996). Data for the water bodies are a set of vector data at a scale of 1:1 000 000 (INEGI, 2000) (Table 1).

**Method**

The detection of convective initiations considered the period from 2010 to 2014 and the months of the boreal summer (April–September). Detection began at 13:00 Local Standard Time (LST) and ended at 20:00 LST. Based on Taylor (2015), for any satellite, an image pixel colder than the threshold cloud-top temperature of $-38^\circ$C (235 K) was considered as possible initiation. An algorithm was applied to eliminate “false initiation” caused by the propagation of cold clouds or even a modest decrease

**Figure 4.** Quantifications of the components of the soil moisture–precipitation feedback (Y-axis) as proposed by Pal and Eltahir (2001): (a) total precipitation, (b) convective precipitation, (c) non-convective precipitation, (d) net all-wave surface radiative flux, (e) net longwave surface radiative flux, (f) net shortwave surface radiative flux, (g) sum of surface latent and sensible heat fluxes, (h) surface latent heat flux, (i) surface sensible heat flux, (j) moist static energy, (k) temperature, (l) specific humidity. As a function of the initial saturation of the soil: 0 = 0%, 1 = 100% (X-axis). Circles represent the months from May to September (letters M, J, J, A, S). All values are spatial monthly means over region (blue square) shown in Figure 3 (Data: NARR (Mesinger et al., 2006)).
in the temperature of an area of stationary cloud cover. If the minimum temperature ($T_{\text{min}}$) within a radius of 30 km fell in the previous hour by more than 10°C per hour ($\frac{dT_{\text{min}}}{dt} \leq -10 \text{ K/h}$), the case was rejected. When detection of the initiations began, it was observed that the pixels had the form of cells or convective systems. A criterion was applied to avoid the capture of repeated initiations. If an initiation was detected within a radius of less than 100 km of a previously detected initiation, it was rejected; this process was repeated until 20:00 LST (Figure 5).

The second part of the method consisted in eliminating the initiations generated by orography, by the ocean, and by water bodies on land. The orographic triggers used were derived from the topography data (GTOPO30); from these was determined the gradient for the whole country; if the initiation had occurred on a gradient greater than 1 km in altitude for every 200 km of longitude ($0.2865^\circ$), then it was rejected. The threshold was established by Taylor (2015) for Europe. Mexico has a complex topography, and the threshold here must be sufficient to suppress orographic convection; a lower threshold can suppress convection initiated by local moisture and heat flows. We used the function “gradientm” of MATLAB, which determines the slope and considers the gradients of topography in both X and Y directions. Once the slope was known for the entire study domain (in degrees), if any initiation was located on a slope greater than the established threshold it was discarded. Therefore, we recorded only those initiations that occurred over flat and shallow-slope regions.

To include the filter for the marine trigger, a land mask function was used, and if any of the initiations detected occurred over the ocean or within 50 km of the coast, that was rejected. Finally, a filter was applied for water bodies on land, such as lakes. For this we used the data for inland water bodies for Mexico, and if any of the detected initiations were within a water body it was ascertained whether this polygon had a surface area of >9 km$^2$; any that exceeded this threshold was rejected. After all filters had been applied, the positions of all the initiations detected were stored.

To analyze the influence of the soil fluxes of moisture and heat in the initiation of convection, the daily anomalies in soil moisture and land surface temperature were determined. Firstly, a monthly climatology of soil moisture was derived from the data from the CCI soil moisture ECV Project for the period 2010–2014. Then a daily soil moisture anomaly (SMA) was calculated. During this process, pixels that corresponded to water bodies, ice or snow were removed by reference to land cover data (MODIS Land Cover type); pixels were also removed if they were situated over complex terrain, by reference to slope determined with GTOPO30. Since the resolution of the soil moisture data was low, the orographic filter used was higher to allow more pixels of soil moisture to be considered. Various thresholds were tested from 0.28° to 5.7° and did not alter the composites of soil

### Table 1. Data sets and features.

| Variable               | Source                                | Spatial resolution | Temporal resolution | Period         |
|------------------------|---------------------------------------|--------------------|---------------------|----------------|
| Cloud top temperature  | PATMOS-x                              | 0.1°               | 1 hour              | 1995–2014      |
| Soil moisture          | CCI Soil moisture ECV Project          | 0.25°              | 1 day               | 1991–2014      |
| Land surface temperature| MODIS/Terra LST/E v5                  | 1 km               | 1 day               | 2000–present   |
| Precipitation          | CMORPH                                | 0.25°              | 3 hours             | 2002–present   |
| Land Cover type        | MODIS Land cover type                 | 500 m              | –                   | –              |
| Orography              | GTOPO30                               | 1 km               | –                   | –              |
| Water bodies           | INEGI                                  | 1:1,000,000        | –                   | –              |
| Wind                   | ERA-Interim                           | 0.25°              | 6 hours             | 1979–present   |

**Figure 5.** Algorithm to convective initiation identification.
moisture anomaly and allowed more humidity data; consequently, the maximum slope allowed was 5.7° (1 km in altitude for every 10 km). Finally, the data were interpolated to obtain a resolution of 0.125° (~12.5 km). Similarly, considering the data of MODIS/Terra LST/E v.5, a monthly climatology was compiled for land surface temperature. In this case, quality control (based on MODIS image pixel quality control flags) consisted in filtering the data that had a mean error of land surface temperature of ≤1°K and an emission error of ≤0.01, and from this climatology the land surface temperature daily anomaly (LSTA) data set was generated.

Considering the position of the initiations, composites of SMA and of LSTA were compiled. For this, the field for anomaly of the day was saved centered on the position of each initiation (±200 km), with the field oriented in the direction of mean horizontal flux of low levels (10 m wind direction) obtained from ERA-Interim (Dee et al., 2011), and from these was determined the dominant wind direction (the mode). Then each anomaly field was oriented in this direction; subsequently, the composites were produced for each month and for the entire period; for each composite, the direction of mean flux of low levels was maintained.

The ForTraCC (Forecast and Tracking the Evolution of Cloud Clusters) technique (Vila, Machado, Laurent, & Velasco, 2008) was used to validate and complement the method described above, considering the month with the most initiations detected, July 2013. This algorithm uses satellite imagery for detecting, tracing and short-term forecasting of MCS (Vila et al., 2008). The configuration of the program used a threshold of size minimum Area ($A_{min}$) >2400 km$^2$ and a Brightness Temperature threshold <−38°C (235 K).

**Results**

In total, 2120 convective initiations were detected in the central region of Mexico. Spatially, this covered more territory in the north-east (Figure 6, top); however, they were more frequent in the south-east, specifically where were recorded the maximum with a total of 44 convective initiations; this is consistent with the large number of storms that occur during summer in that region. The soil of the south area (Figure 6, top and blue square in Figure 3) is usually saturated (we have a cell that has more than 15 initiations). We expected this pattern from the previous analysis; we selected this region to analyse the feedback soil moisture–precipitation (Figure 4), because it is a region with a higher soil moisture content and the composites show the role of soil moisture in initiating convection, as suggested by Pal and Eltahir (2001). On the other hand, in the northern regions of the country the zones of initiation are present in regions with lower soil moisture content, and because we had removed the initiations caused by topography, they should be associated with the moisture anomalies of the surroundings (heterogeneity) and the local circulations (the hypothesis). Therefore, they should be interpreted as regions with greater response to the heterogeneity of the soil.

With respect to the temporal distribution, July was the month with the greatest mean number of initiations; this is a month with high temperatures and when the soil moisture increases. The daily cycle of convective initiations is bimodal: the first maximum is during 14 or 15 LST and the second during 18 or 19 LST (Figure 6, bottom).

**Trajectory of the convective systems of July 2013**

The MCSs have a mean velocity during their trajectory of 28.3 m/s. During the maturation stage, the MCSs have a mean minimum temperature of −58°C (215 K) and a mean area of 4500 km$^2$; the systems have a mean duration of 2.4 h, although most last for 1 h. Even though these data result from just one case study they can be of great help in generating a criterion for convective initiation for the Mexican land mass.

The algorithm ForTraCC is designed to detect cloud clusters, and therefore detects large-area systems. In contrast, the method proposed by Taylor considers pixel by pixel, taking into account a larger number of pixels as probable convective initiations, and thereby capturing smaller-scale systems also; this is a desired feature, since it allowed us to review the link between convective initiation and local flows (Figure 7). ForTraCC validates the initiations detected by Taylor’s method, since their spatial distributions are similar (Figure 7).

**Influence of soil moisture**

Starting with these 2120 initiations, the influence of soil moisture on the convective initiation was analyzed by use of the composites of SMA and LSTA. The composite of the soil moisture anomaly (Figure 8, left) indicates that the initiations occurred in regions with moisture greater than the mean, but with wetter surrounding areas.

The composite of daily anomalies in land surface temperature (Figure 8, right) reveals a decrease in the surface temperature over the region of initiation. There is also an inverse relationship between the SMA and the LSTA. In fact, when the mean gradient in the direction of mean flow (downwind) is determined for the SMA, it is +0.0137%/km in the region of initiation and for the LSTA it is −0.0157 K/km. For a more specific analysis, the composites were obtained month by month.

Since convective initiation varies over scales from month to days, and can be influenced by tropical and
subtropical processes (Taylor, 2015; Taylor et al., 2011), such as the North America Monsoon and Midsummer Drought, the monthly average was removed: the monthly climate was determined and from that the daily anomaly was calculated (see section 6 of supplementary information for more details). May and September were the months that showed the greatest contrast to the average composites, May differs (Figure 9), in that it is drier and warmer, so we expect that the flows of sensible heat and the humidity of the surrounding areas would be important for the generation of convective initiations.

For September (Figure 10) in the initiation region, the soil moisture anomaly is positive and the surface temperature anomaly is negative, which is similar to Figure 8. Even though the decrease in temperature in the direction of mean flow (downwind) is not clear, it is to be expected that the soils are already sufficiently wet to generate initiations.

The distribution the SMA gradient with normal density distribution function (Fig. S4, see supplementary information) shows the initiations are preferably for positive anomaly of SMA as calculated previously. However, there are still many initiations with negative gradient. Then there are different patterns that can produce homogeneity in the SMA (and LSTA) composite, but these changes of SMA gradients may be linked to the

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Figure 6. Convective initiations detected during summers (April–September) of 2010–2014 (top). Number of initiations per hour and per month for the summer months (April–September) of 2010–2014 (bottom).
weak and strong winds as Taylor (2015) and Froidevaux et al. (2014) describe. To analyse the change of SMA’s gradient linking to weak or strong winds, we have calculated the mean of SMA as a function of the wind direction (Fig. S5 see supplementary information). For weak winds (wind speed <5 m/s) and strong winds (wind speed >5 m/s). It shows evidence of linking between background wind and SMA gradient; the weak winds are associated with positive SMA gradient over initiation zone meanwhile the strong winds are related to negative SMA
gradient. Thus, it is found two different SMA patterns (weak and strong winds) that explain the homogeneity of Figures 8, 9, and 10, because if they are combined the signal is reducing. Therefore, the background wind plays an important role in the convective initiation driven for soil moisture heterogeneity, leading to more or less conditions for the development of convection. Further discussion is presented in the supplementary material.

Sensitivity of the initiations to the change of soil wetness

The contribution of the preceding rainfalls to the initiations was examined; the CMORPH data were used to calculate the rain accumulated in 30 days preceding each initiation. To gain some insight into the humidity in the region of initiation, the mean rainfall over 2°x 2° grid centered on the initiation was calculated. The database of initiations was matched in quartiles according to the precipitation accumulated in 30 days preceding the initiation. The resultant quartiles (Q) are as follows: (Q1) rain < 25 mm, 25 mm ≤ (Q2) rain < 57.7 mm, 57.7 mm ≤ (Q3) rain < 117.7 mm and (Q4) rain ≥ 117.7 mm.

In principle, as expected, the driest quartile (Q1, Figure 11(a)) is the warmest. LSTA values over the initiation zone decrease as rain increases, and they become negative from quartile Q3 to Q4. Regarding the spatial variability for LSTA around the point of initiation, there is a negative gradient on the LSTA initiation zone in the direction of the wind. This negative gradient is more evident in quartiles Q2 and Q3. The SMA and LSTA are negatively correlated; however, this negative correlation is not clear in all regions, which may be due to the difference in resolutions (1 km for LSTA and 0.25° for SMA), as Taylor (2015) also found. The SMA shows a positive gradient on the initiation zone in Q1, Q2 and Q4, and prior to the initiation zone in Q3. This defines the initiation zone with positive gradients of SMA in the wind direction, showing the importance of the SMA pattern for the generation of local circulations and the contribution of the moisture fluxes of the surroundings for the convective initiations in dry locations (Q1). The generated initiations and their consequent precipitation strengthen the negative gradients of LSTA and decrease the negative anomaly of SMA on the initiation zone (Q2). This pattern is similar to previous findings, with less-dry regions around the zone of initiation and a positive gradient of SMA over the initiation zone (Froidevaux et al., 2014; Taylor, 2015; Taylor et al., 2011). For Q3, the SMA increases owing to the contribution of the previous rains; however, the SMA gradient occurs before the initiation zone, and this can be the cause of winds (possible weakening) that drag the precipitation of the convection (Froidevaux et al., 2014). This implies that the saturation of the soil moisture in the initiation zone begins to have the main role in the generation of the initiations. The above shows that the pattern of heterogeneity of the SMA changes as soon as the soil becomes saturated and the rainfall dampens the soil and distributes more to the atmosphere, and this in turn generates higher available humidity for convection and rainfall, generating a positive soil moisture–precipitation feedback.

Surface wind vs the planetary boundary layer mean wind

Calculation of the composites considered the mean wind within the planetary boundary layer. The aim was to capture a higher contribution of humidity and identify the direction of cloud movement. A comparison of the effect of airflow on the boundary layer (Figure 12) shows that most of the precipitation occurs around the initiation zone, whether considering only the surface wind or the wind in the boundary layer. In both cases, the nuclei with greater precipitation occur when the initiation zone is overcome, that is over a wetter soil, which coincides with the mean wind direction.

At least for the month of April in 2010, the composite in which only the surface wind was considered, there is a nucleus of precipitation exactly facing the initiation
zone and one preceding the initiation zone. Therefore, it seems that the soil moisture is dragged by the wind at low levels towards the initiation zone (Figure 13), where it contributes to the generation of convective cloud, indicating that the flows of soil moisture determine the convection in tropical regions.

**Discussion and conclusions**

The role of the soil in convective initiation still poses challenges. This paper shows that there is a pattern, in general, where surrounding areas are moister than the initiation regions. Certainly, the humidity anomaly in the initiation zone is positive, which suggests that there are other dynamic processes that modify the initiation zones, probably the effect of the wind (background wind), as proposed by Taylor (2015), Froidevaux et al. (2014), and, additionally, the saturation of the soil as more rain occurs. This variation can be observed in the patterns of May and September which are months of transition in the summer for most of Mexico (May is a month with a significant increase in temperature and September a month with abundant rain). Therefore, the hypothesis would be, the effect of the wind and the increase of rains during the summer may be generating these variations and a possible positive feedback effect (Froidevaux et al., 2014). The convective initiation is generated on dry soil (May), but the convective cell propagates on humid soils, where they precipitate and increase the anomaly, generating conditions enhanced convective initiations. Froidevaux et al. (2014) suggest examining
the role of the average tropospheric flow. Notably, in the Figure 11, you can see a change of LSTA gradient and in the initiation zone presents a negative gradient downwind, this expected pattern, a colder (wetter) after the initiation zone and a soil moisture heterogeneity. This shows the importance of further investigation of the impact of surface fluxes on convective initiation during the summer in Mexico, taking advantage of the increase in resolution of the satellite products, and of verifying what the studies carried out with models suggest (Adler, Norbert, & Leonhard, 2011; Froidevaux et al., 2014).

Topography is one of the main factors taken into account in the methodology. It is not a simple procedure, since the topography of Mexico is very complex, particularly in the central region. In addition, the vegetation cover has not been taken into account, and its contribution should be considered in future research. There is no straightforward way to explain all the processes involved. However, we have identified that the convective initiations are influenced by the surface fluxes of heat and humidity in the central region of Mexico. The mesoscale flows at low levels significantly influence the convective initiations, since they drag the soil moisture towards the initiation zones. In general, the initiations occur preferentially in anomalously wet regions, but adjacent to a wetter and colder region. The soil moisture anomaly is negatively correlated with the land surface temperature anomaly, and it is a good proxy for soil moisture, albeit the inverse. In fact, the initiation zone is typified by a decrease in the land surface temperature and an increase in soil moisture along the wind direction.

The preceding precipitation is important in the first months of the summer (April–June), since the rainfall gradually increase in those months. The surface humidity of the surroundings is important in those months because of the contribution of humidity that is dragged to the initiation zone. This rainfall contributes to the saturation of the soil, increasing the humidity available for the occurrence of initiations in the following months.

To consider the mean flow at low levels is similar to using the mean flow in the boundary layer, at least for the month of April, a month of transition between
winter and summer. Therefore, it is again demonstrated that the flows at the surface interact directly in the mesoscale circulation and are determinants for the activation of convection in the central region of Mexico.

Acknowledgments

The National Council of Science and Technology (CONACYT) for the first author’s MSc. scholarship 419902 and our very great appreciation to Dr Luis Augusto Toledo Machado for providing the ForTrACCG nowcasting model.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was supported by the Consejo Nacional de Ciencia y Tecnologia (CONACYT) Mexico under grant 419902.

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