Recovery of oil palms (*Elaeis guineensis* Jacq.) affected by spear rots

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Abstract

Spear rot or PC (for the Spanish name *pudrición del cogollo*), known locally in Costa Rica as '*flecha seca*' is a disorder that affects the development, physiology and yield of the oil palm. It is associated with the deterioration of the fine root system under unfavorable weather and soil conditions. The disorder is not lethal and most palms can overcome the symptoms after a variable period. The hypothesis tested in this work was that it is possible to reduce the severity of the symptoms and eventually the recovery period, using practices that improve the physical and microbiological conditions of the soil to stimulate root growth and improve the nutritional and energy status of the palms. The response obtained was measured using data on morphology, growth, physiology and yield of treated and control palms. In addition, the physical, chemical and microbiological properties of the soil were characterized. To reduce the genetic effect, the study was done with a particular clone that was known to be highly susceptibility to the disorder and that required a long period to recover from the symptoms. The study began when the palms were 28 months old and continued for two years.

Two edaphic units (Coarse, Aquic Eutrudept and Medial, Aquic Eutrudept) were identified at the experimental site; where the terrain was irregular, the soil had poor drainage in the first 30 cm, high bulk density, low hydraulic conductivity and few air spaces. All these physical properties favored the presence of standing water during prolonged periods. At the end of the rainy season of 2012, a deterioration of the fine root system was observed when the soil volumetric water content increased above 40%. Imbalances were found between some nutritional elements and in the physiology of the affected palms and later on appeared the typical aerial symptoms of PC: chlorosis and drying of the leaflets at the base of the new leaves and other drying and decay of the petiole bases.

The palms that received the recovery treatments showed a remission of symptoms in approximately 18 months, while the control palms were still showing major PC symptoms after two years. Visual (vegetative) recovery was associated with the remediation of the physical, chemical and microbiological properties of the soil, which in turn improved root mass and root health. The nutrient content in the leaves (N, Fe, S and K), root density, trunk height, photosynthesis, fruit production and bunch oil content increased significantly in the recovered palms compared to the untreated controls.

Nutrient application (to the soil and the aerial part), and surgical removal of affected tissues in particular, helped to obtain more rapid recovery. It was evident that the removal of necrotic tissue from the petiole bases extended the longevity of the leaves. Nevertheless, the effect sought with the systematic removal of the inflorescences (for the purpose of diverting assimilates to the roots) was not clear.

We conclude that the recovery from PC should focus on the regeneration and maintenance of a healthy root system and that the possibilities for success increase when symptomatic palms are treated early. However, emphasis should be placed on prevention, which means taking prompt measures to minimize the negative effects of brusque changes in environmental conditions that could stress the plants. In addition, there should be early detection and immediate correction of any factor or factors (primarily physical, chemical and microbiological aspects of the soil) that could negatively affect the maintenance of a healthy root system.

Keywords: *Elaeis guineensis*, pudrición del cogollo, spear rot, recovery, predisposition

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Introduction

Spear rot or '*pudrición del cogollo*' (PC) is a disorder that affects the development, physiology and yield of the oil palm. Initial symptoms of PC on the foliage; normally include chlorosis of some leaflets at the base of some of the recently opened leaves. Some leaflets may show necrotic lesions while forming part of unopened leaves (spears), which can end up as generalized drying or decay. Occasionally, the lesions may penetrate deeply into the meristem region, causing the death of the palm. PC symptoms generally occur in soils with poor aeration, acid-base imbalances, and impoverished microbiological activity. The appearance of the disorder may be preceded by changes in the precipitation pattern (very dry seasons followed by abnormally heavy rainy seasons) associated with previous conditions favorable for high bunch production (Albertazzi et al. 2005, Chinchilla & Durán 1999, Torres et al. 2014).

The efforts to associate the entire range of PC symptoms with a single pathogen have not yielded definitive results. There have been several candidates (fungi, bacteria, viroids, etc.), and with some of them the rot symptoms have been replicated, but not the entire range of symptoms that the syndrome encompasses. Nor have the treatments to attack the possible pathogens given conclusive results. The role of the many organisms associated with PC appears to be opportunistic, attacking palms that have suffered some kind of stress sustained over time, predisposing the palms to infection (Chinchilla 2008, 2010).

The ideal situation would be to take effective measures to prevent the palms from becoming affected, and the experience with PC suggests that the identification and prompt correction of situations that negatively affect the root system and the energy status of the palm is a sound strategy. Nevertheless, given that many plantations are already affected by PC, this work was done to test the hypothesis that if an affected palm (particularly a highly susceptible clone) received special attention, its vegetative and reproductive recovery could be accelerated and that both processes were related to the recovery of the root system.

Materials and Methods

The study was carried out in a plot planted with an oil palm clone (Alvarado et al. 2006) known for its high susceptibility to PC and long recovery period. The palms were 28 months of age, planted at a density of 160 palms/ha in 2010. The climate of this Southern Pacific region of Costa Rica is wet (fewer than three relatively dry months), with annual precipitation above 4,000 mm. The rainiest periods occurs between May and November, with precipitations of 800 mm or more per month. The soil is of alluvial origin, with sandy clay textures predominating and an *udic* moisture regime (less than three dry months per year). The study area was located in the vicinity of the alluvial plain sediments of the Coto-Colorado River.

Field information was obtained between November 2012 and June 2014, a period that included two periods with less rainfall (November 2012 - April 2013: monthly average 160 mm, and December 2013 - April 2014: monthly average 140 mm). During the intermediate rainy period (May-November 2013), an average of 450 mm/month was recorded. The aerial environment was measured using an automatic weather station (Watch Dog), located 2 km away.

At the start, the palms were grouped into three categories according to the severity of the PC symptoms that were observed in November 2012 (Fig. 1).

Fig. 1. Categories according to the severity of PC symptoms in November 2012 in the clone (beginning of the study). Left to right: PC 0: Healthy palm; PC 1: Advanced PC symptoms; PC 2: Severe PC symptoms (note the broken lower leaves). The progress of the symptoms was very rapid in this clone and recovery was slow; therefore, it was not very common to find palms with symptoms that could be characterized as intermediate between advanced and severe.

The palms deemed healthy (PC 0) had a normal appearance with no chlorosis or drying. The PxS index (petiole cross-section) showed the normal trend for an increase in the newest leaves and the root system appeared healthy. Leaves on the palms in the advanced symptom category (PC 1) showed partial to extensive chlorosis and drying of the leaflets on new leaves, accumulation of spear leaves, gradual reduction of the PxS index in new leaves, and a reduction in root density. In the severe symptom category (PC 2), the palms showed extensive chlorosis, drying of the leaflets on new leaves, presence of rot at the petiole bases, petiole breakage on lower leaves, accumulation and rotting of spear leaves, gradual reduction of the PxS index in new leaves, reduction of root density and discontinuous reproductive cycles.

Recovery treatments

Each one of the eight treatments for recovery were applied to a group of 10 palms (not necessarily neighbors), that were initially placed in the three symptom categories indicated above (Table 1 and Fig. 1).

Table 1. Treatments for recovery in an oil palm clone. The palms were initially classified into three categories of spear rot severity (*'pudrición del cogollo'* or PC) (Figure 1)

PC	Treatment	Agrochemicals on the foliage	Soil remediation	Removal of inflorescences	Surgical removal of affected tissue
0	T1	■	■		
	T2	Healty control palms			
1	T3	■	■	■	■
	T4	■	■		■
	T5	Affected control palms			
2	T6	■	■	■	■
	T7	■	■		■
	T8	Affected control palms			

The shaded area indicates the treatment applied.

The application of agrochemicals to the foliage was done in an attempt to improve the palms' natural defenses (Foliveex polysaccharides and multi-minerals, Kmax, Mgmax and Alexin). In addition, starting in February 2013, applications of other fertilizers were done to improve the nutritional status of the plants (urea, potassium sulfate, magnesium sulfate and sodium pentaborate).

Surgery was carried out to remove necrotic tissue and prevent additional damage by opportunist pathogens. Special emphasis was placed on eliminating affected tissue at the petiole bases, because this was the most conspicuous symptom on affected palms. Kilol, Sevin, Metalaxil MZ, Cosmoin and Cosmoagua were applied to the wounds. Subsequently, the commercial sealer Agrofixer was applied. The elimination of young inflorescences of both sexes (referred to as 'ablation' in the rest of the document) was done monthly over 18 months for the purpose of inducing the partition of photosynthates toward vegetative development.

The soil remediation treatment was applied with the objective of improve the physical properties, reduce the soil volumetric water content, and increase microbial activity and nutrient uptake. These tasks were concentrated near the base of the plant (corona or circle) to facilitate the evacuation of surface water. In addition, the compacting of the soil surface was reduced in an area within a two meter radius around the base of the trunk, followed by the incorporation of humitec 80, Kmag, zinc sulfate, and compost consisting of empty oil palm bunches, split into three applications of 200 kg every six months. In general, the treatments were chosen based on previous experience dealing with this disorder (Chinchilla & Durán 1999, Albertazzi et al. 2009b, Chinchilla 2010).

Site characterization

The ground contour was determined using a clinometer (Suunto, Mod. Tandem-360PC) at 30 points, which were georeferenced using a GPS unit (Garmin 62 SC) in January 2013. The contour map was created using the Surfer program version 8 (Golden Software) and the classification guide of the National Soil Survey Center (Schoeneberger et al. 2002).

The physical properties of the soil were measured in November 2012 toward the end of the rainy season. Effective depth, bulk density, total porosity, hydraulic conductivity, gravimetric humidity and texture were determined. The changes in the soil volumetric water content were determined monthly at 80 cm depth in a point around 20 palms distributed throughout the area, using a TDR (time domain reflectometer, Eijkelkamp, Mod. MP406-ICT).

Soil nutrient content in the first 70 cm of the soil profile was determined in May 2013 (580 mm of precipitation) and in November 2013. At the end of the 2013 rainy season (November), microbiological diversity was documented in the rhizosphere of five control palms and five palms where soil remediation was done. The sample was taken from the first 10 cm of soil depth at one meter distance from the base of the trunk. The DNA of the phylogenetic groups and genera of beneficial and potentially pathogenic microorganisms were determined and their expression was quantified using real-time PCR (Thermo Scientific, model PikoReal-96) using SYBR Green probes.

Vegetative and production variables

Ten palms were measured in each one of the eight treatments in December 2012, February, May and October 2013 and March 2014: trunk height and number of leaves with less than 30% of the area showing symptoms, rachis length and PxS for leaf No. 9.

Evaluations of root density were done for seven palms per treatment in June, September and November 2013 and in January and May 2014. The samples were taken at 0-15 cm and 15-30 cm of depth, at distances of half, one and two meters from the base of the trunk with a 750 cm^3 auger (Eijkelkamp). The roots extracted were washed with water, their total length was quantified, and the result was divided by the volume of the auger cylinder to obtain root density (cm/cm^3), using the "WinRhizo" software (Gutiérrez et al. 2014).

Bunch production was quantified for the same 10 palms for certain treatments (T1, T2, T4, T5, T7 and T8: treatments without the removal of inflorescences, Table 1). The data correspond to the sum in kilograms of fresh fruit produced per palm in the period from June 2013 to June 2014. Bunch oil content was determined in a sample of 11 bunches from the same treatment groups in November 2013. Leaf nutrient content was determined in May 2014 in a sample of the basal, medial and distal leaflets of leaf No. 9 in five palms per treatment.

Physiological variables

Due to the dynamic nature of PC and the effect of the treatments, the severity of the symptoms changed over time and some initially affected plants were subsequently classified as recovered (healthy) or as having more severe symptoms. The initial classification (PC 0, PC 1 and PC 2) was used to define the group of plants to which the treatments were applied, to make statistical comparisons of growth and production, and to prepare the severity curves. During the physiological measurements, the palms received a new classification according to their severity at the time and palms that apparently were recovered (PC 0) or with recovery underway (PC 1) were compared. The severe symptom category (PC 2) was taken from control palms that were healthy initially and became affected during the course of the work. In each new category of PC severity, measurements were taken on five palms regarding the physiological condition of the basal, medial and distal leaflets on leaves in positions 1, 9 and 17 in the phyllotaxy. The measurements were done in the dry

(February-March) and rainy (September-October) seasons of 2013 and the dry season of 2014 (March).

The water potential was taken using a pressure chamber Scholander (Mod. PMS 1000, Oregon) from 5:00 to 6:00 am and from 11:00 am to 1:00 pm. Photosynthesis was measured between 7:00 and 15:00 hours, with one-hour intervals between each round. For this purpose, a portable system was used to measure photosynthesis (Li-6400XT, LiCor Biosciences, Lincoln, NE) by quantifying photosynthetically active radiation (PAR), net photosynthesis (A), stomatal conductance (g_s) and transpiration (E) of the medial leaflets of leaf No. 9.

Data analysis and interpretation

Each one of the 80 palms evaluated was considered as an experimental unit or replicate. Treatments T1 and T2 (initially healthy palms) were treated separately from the rest and compared using a *t*-test. The statistical analysis of growth variables for categories PC 1 and PC 2 (as for November 2012), were done using data from March 2014 (16 months after the treatments were initiated) and two sources of variation were considered: the initial PC severity and the treatments for recovery. The significance of the difference between means for initial PC severities was verified using the minimum significant difference, while treatments T3 and T4 (advanced symptoms, complete treatment with and without ablation, respectively) and T6 and T7 (severe symptoms, complete treatment with and without ablation) were compared against their respective controls (T5 and T8), using Dunnett's test ($P < 0.05$).

Production variables and bunch characteristics were analyzed using a *t*-test, in which the means of treatments T4 and T7 (advanced and severe symptoms with complete treatment without ablation, respectively) were compared against the respective controls (T5 and T8) ($P < 0.05$). For the physiological variables, an analysis of variance was done between the three categories of PC severity using a multiple comparison of all the pairs of means using the DGC test ($P < 0.05$).

Results

Climatic conditions

The average rainfall per month between November 2012 and April 2013 was 131 mm, and 136 mm in the next low rainy season between December 2013 and April 2014. During the rainy season, precipitation fluctuated between 445 and 560 mm/month. Other climatic data are shown in figure 1. The previous year (2011) had been very rainy (5900 mm versus. 3343 and 3350 mm in 2013 and 2014, respectively).

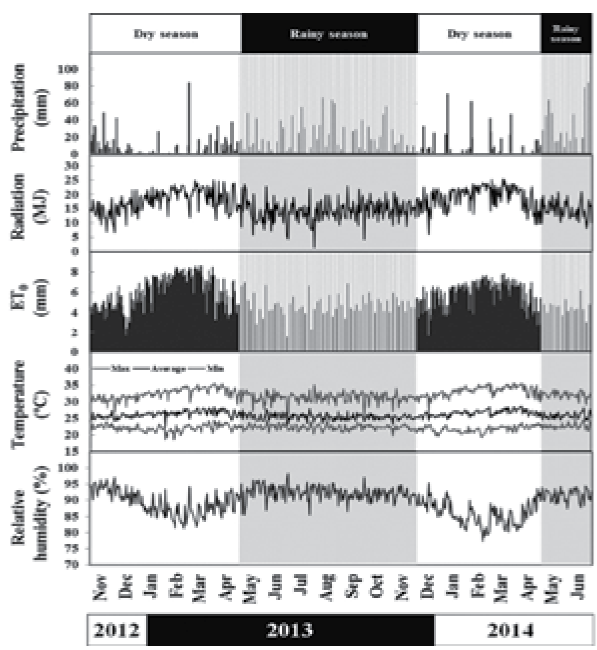

Fig. 2. Precipitation, total solar radiation, potential evaporation (ET_0), temperature and relative humidity of the air, were measured daily between November 2012 and June 2014. The periods with less rain are labeled as 'dry season' in the figure.

Geomorphology and soil physics

The soil formation process in the study area varied according to the size of the particles deposited in the different alluvial episodes and the topography of the terrain (Figs. 3, 4). The Coarse, Aquic Eutrudept edaphic unit (low terrain: 30% of the area) was characterized by the predominance of larger particles, while in the upper land (Medial, Aquic Eutrudept), finer textures prevailed (60% of the area). The low zone presented moderately slow drainage, while in the high zone, drainage was slow to very slow.

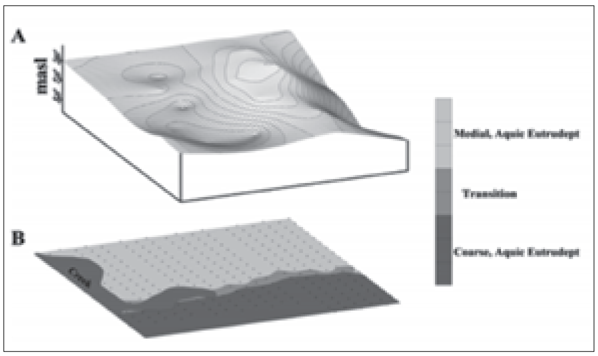

Fig. 3. *Above.* Variations in the ground contour. *Below.* Spatial distribution of the edaphic units. The diagrams were generated from 80 observations at sites with palms selected in the study and the description of two soil pits (Fig. 4). The interpolation was done using the Kriging method and the Surfer 8 program.

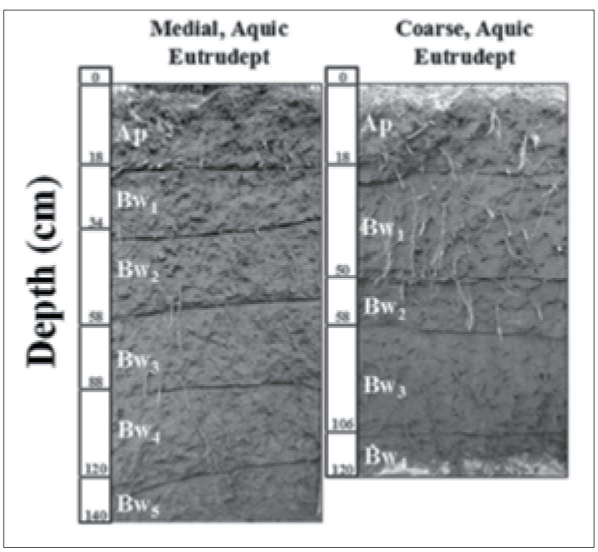

Fig. 4. Effective depth, nomenclature of the horizons and taxonomic classification of the soil in the two edaphic units of the study area. Both units showed drainage limitations at surface level (Ap horizon) (classification according to USDA soil taxonomy).

Although bunch yield potential was high in the two edaphic units identified, the limitations of the site were evident at surface level (Ap horizon), particularly in the Coarse, Aquic Eutrudept unit, where porosity and hydraulic conductivity were lower, which favored moisture saturation (Table 2).

Table 2. Physical properties of the two edaphic units of the area where the treatments for the recovery of palms with PC were implemented. The values are weighted averages taking into account the depth of the horizons in each one of the profiles. Nov. 2012

Variable	Edaphic unit		Ap horizon	
	Medial, Aquic Eutrudept	Coarse, Aquic Eutrudept	Coarse, Aquic Eutrudept	Medial, Aquic Eutrudept
Effective depth (cm)	145.0	115.0	18.0	18.0
Bulk density (g/cm^3)	1.1	1.1	1.3	1.0
Total porosity (%)	48.0	51.1	39.2	51.1
Air spaces (%)	13.2	22.6	12.2	22.1
Hydraulic conductivity (cm/h)	0.4	1.1	1.0	1.1
Gravimetric water content (%)	31.2	25.0	21.2	28.5
Texture	sandy clay loam	sandy loam	sandy loam	sandy clay loam
Clay (%)	29.6	10.6	15.0	25.0

PC symptoms in the clone

Chlorosis normally started on the distal part of the young leaves and from the tips of the leaflets progressing toward the base. Nevertheless, it could also followed the opposite pattern (the first leaflets showing the symptom were those at the base of the leaf). Eventually, the chlorosis degenerated into necrosis from the distal end of the leaflets. Necrosis of the petiole bases was severe, often causing the leaves to break in that section; plants could therefore lose 30% or more of their leaves prematurely. The fruitlets did not fill out normally and became dehydrated (Fig. 5).

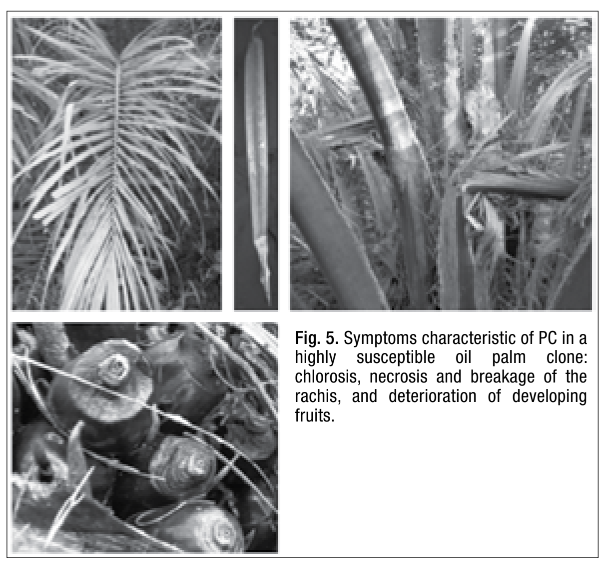

Fig. 5. Symptoms characteristic of PC in a highly susceptible oil palm clone: chlorosis, necrosis and breakage of the rachis, and deterioration of developing fruits.

Spatial distribution of PC and soil volumetric water content

The capacity to evacuate superficial water (runoff) was different in the two soil types, even though they shared a similar drainage infrastructure. At the start of the rainy season in May 2013, the incidence of PC increased in the lower area and this was associated with the increase in the soil volumetric water content (SVWC). The increase in SVWC to 42% as precipitation escalated between June and November, was also associated with the 'spread' of PC in nearly the entire area. In December 2013, when VH SVWC fell to 30%, PC incidence diminished and a clear trend toward recovery from the symptoms in the affected palms was noted, particularly in those that received the treatments. By June 2014, the only palms that still had clear PC symptoms were the controls and the originally healthy palms that had progressively became affected (Fig. 6).

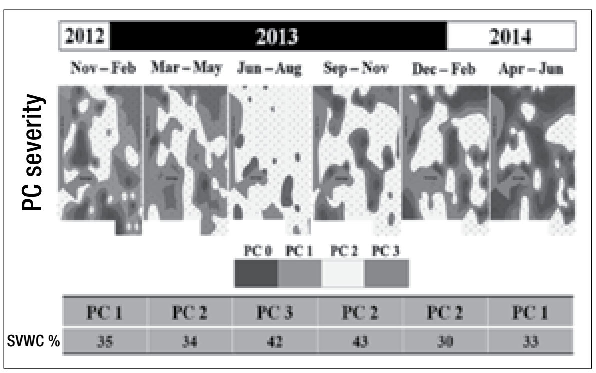

Fig. 6. Progress of PC over time (average of three months) in relation to changes in the soil volumetric water content (SVWC, %) at 0 to 80 cm of depth. SVWC diagrams were prepared based on measurements over time at 20 sampling points and the level of PC severity in 80 palms. The interpolations were done using Kriging and the Surfer 8 program.

Chemical properties of the soil

The soil was classified as eutric due to its high calcium (>15 cmol (+)/L) and magnesium (> 2.5 cmol (+)/L) contents. With the soil remediation treatment acidity and acid saturation were reduced in comparison with the untreated control soil (2.32 to 0.23 cmol (+)/L and 8 to 0.7 %, respectively). The amount of Mg increased from 5.15 to 6.65 cmol (+)/L, K content rose from 1.39 to 7.16 cmol (+)/L, and the effective cation exchange capacity of the soil increased from 29.16 to 32.93 cmol (+)/L. However, with the five-fold increase in K content, the cation ratios Ca/K, Mg/K and (Ca+Mg)/K fell below optimum levels.

Microbiological properties of the soil

One year after (Nov. 2013) the start of the application of the recovery treatments, 29 phylogenetic groups were identified in the rhizosphere of the untreated control palms, of which 26 were potentially pathogenic and three corresponded to beneficial microorganisms. We found high concentrations (above 300 pg DNA/ml of soil) of *Thielaviopsis* sp., *Phytophthora* sp., *Fusarium* sp., *Pseudomonas maculicola* and *Pseudomonas* sp. High concentrations of α and β-proteobacteria and *Bacillus* sp., were determined to be the main beneficial microorganisms (Fig. 7).

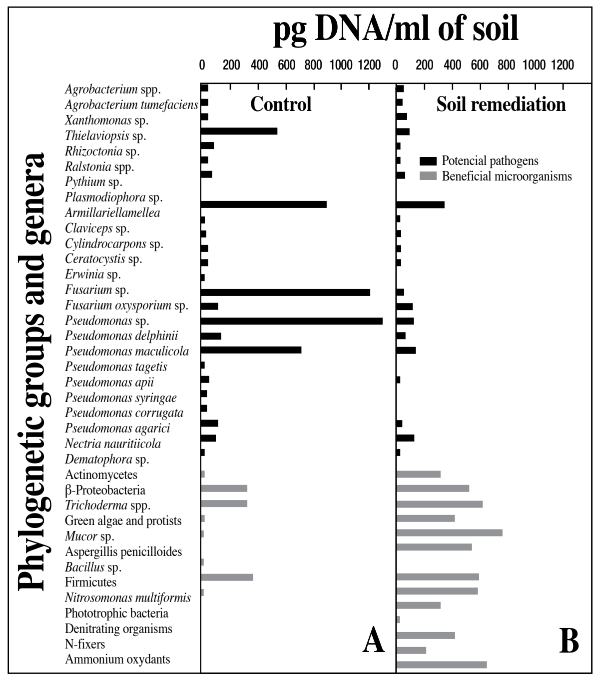

Fig. 7. Abundance expressed in pg DNA/ml of soil, for the main phylogenetic groups and genera present in the rhizosphere 12 months after the application of the recovery treatments. A: Absolute controls and B: Soil remediation. The results correspond to the rainy season of 2013 (November), based on a sample consisting of five palms for each treatment; the samples were taken in the first 10 cm of soil depth, one meter from the base of the trunk.

With the soil remediation treatment, the diversity of beneficial microorganisms in the rhizosphere rose from 3 to 12 genera, which is equivalent to an increase of 1065 to 6000 pg DNA/ml of soil. The principal beneficial microorganisms identified were: Actinomycetes, α and β-proteobacteria, *Trichoderma* spp., *Mucor* sp., green algae and Protista, *Bacillus* sp., *Streptomyces* spp., Firmicutes, *Curtobacterium* spp., *Nitrosomonas multiformis* and nitrifying and ammonia oxidizing bacteria, while the concentration of potentially pathogenic groups was notably reduced, identified mainly as *Pseudomonas* sp., *Fusarium* sp. and *Phytophthora* sp. (Fig. 7).

Response to treatments

Initially, in November 2012, three groups of PC severity were distinguished: healthy palms, palms with advanced PC symptoms and palms with severe symptoms of the disorder (Fig. 1). In May 2013, at the height of the rainy season (precipitation: 550 mm), all the palms selected, including the initially healthy controls, showed PC symptoms. During the start of the 2014 season with less precipitation, all the affected palms that received special care showed a progressive reduction of symptoms and were apparently healthy in June of that same year (Table 1 and Fig. 8).

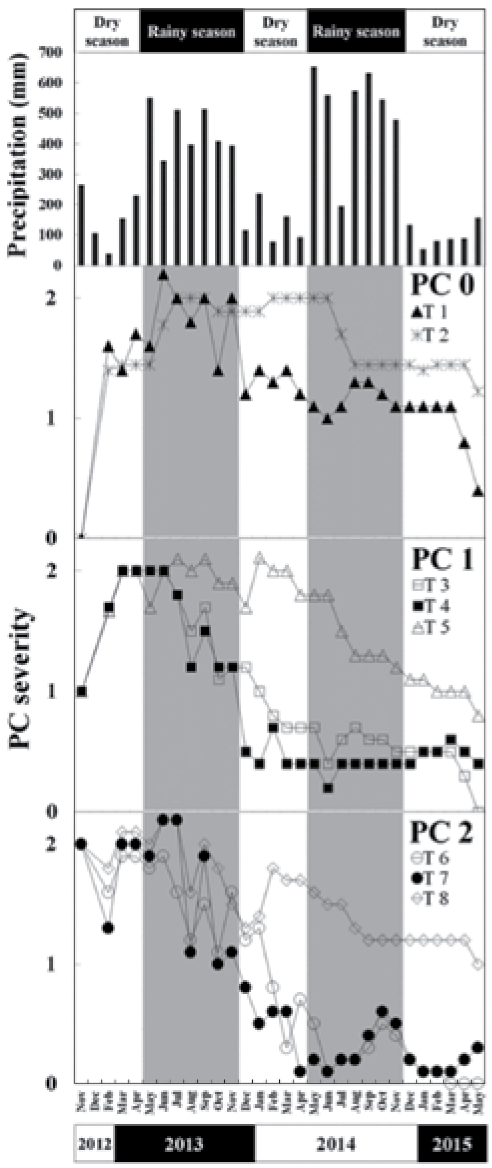

Fig. 8. Severity of the PC disorder over time based on initial PC symptoms (November 2012) and the recovery treatment. PC 0, PC 1 and PC 2 describe the initial condition of the palms: healthy, with advanced symptoms, and severe symptoms, respectively. T2, T5 and T8 = control; T3 and T6: complete treatments for recovery with ablation; T4 and T7 complete treatment without ablation (Table 1).

Root density

Changes in the aerial PC symptoms over time were related to the dynamic of the root system. The treated palms showed a significant increase in root density one year after the treatments were initiated, which was associated with an increase in the PxS of the new leaves and even with the height of the plant. The remission of visual PC symptoms 19 months after treatments began (June 2014) was preceded by a highly significant increase ($P < 0.01$) in root density. The differences between the controls and the treatments with or without ablation were 16 cm/cm^3 and 14 cm/cm^3 in palms with advanced and severe symptoms, respectively (Fig. 9).

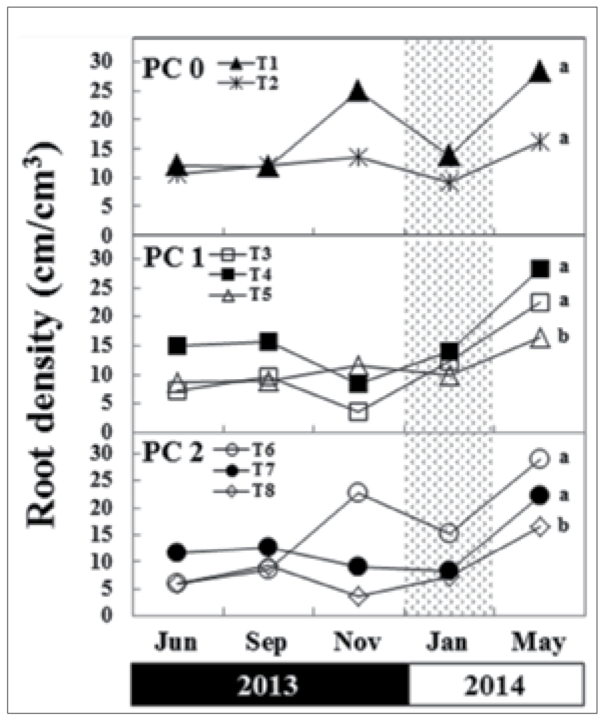

Fig. 9. Root density (cm/cm^3) according to PC severity and the recovery treatment. Samples were taken from 0 to 30 cm depth, at 0.5, 1 m and 2 m from the base of the palm trunk. The comparison between PC severities were performed using the minimum significant difference. Treatments that included the application of agrochemicals and soil remediation with and without the removal of inflorescences were compared with the respective controls using Dunnett's test ($P < 0.01$). Means of seven samples per treatment per evaluation date. T5 and T8 = controls; T3 and T6 equivalent to the complete treatment for recovery with removal of inflorescences; T4 and T7, complete treatment without removal of inflorescences (Table 1).

Vegetative growth

Trunk height, with an increase of 25 cm at the end of the evaluation period, was higher in palms that received the complete treatment including ablation, in comparison with the control treatment. Other variables, such as the number of leaves and the PxS index did not show significant differences between treatments, except at the start of the rainy season in

May 2013, when palms with the complete treatment had a larger PxS than those treatments where ablation was not applied and the controls. However, there was greater vegetative development (larger PxS and longer rachis) in initially affected palms that were treated.

Physiology

Water potential (Ψ_H) was similar among the different treatment groups during the period with less rain, but it varied during the rainy season of 2013, particularly during the afternoon hours, when leaves Nos. 1 and 9 of the recovered palms and those with advanced symptoms (PC 0 and PC 1, respectively) showed a lower Ψ_H than the palms with the more severe symptoms ($P < 0.05$). During the morning of the rainy season of 2014, the leaf No.9 on of palms with advanced symptoms showed a significant reduction in Ψ_H. In the dry season of 2014, leaves Nos. 1 and 9 of the recovered palms and the ones with severe symptoms showed significantly higher water potentials in comparison to palms with advanced symptoms (Fig. 10).

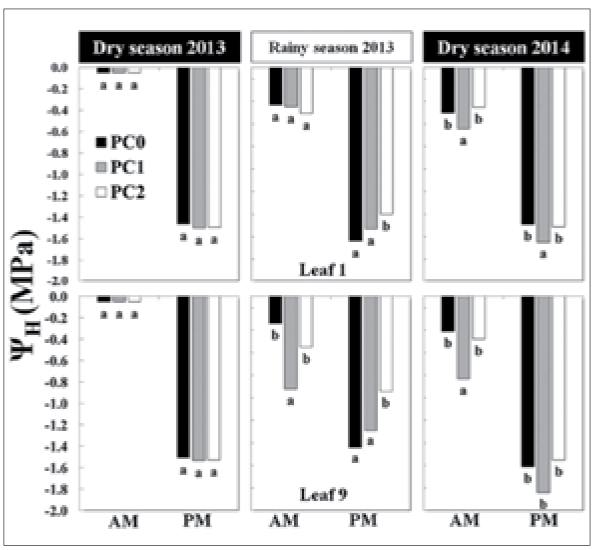

Fig. 10. Water potential (Ψ_H) of leaves No. 1 and 9 in the three categories of PC severity. Measurements between 5:00 and 6:00 am and 11:00 and 1:00 pm in February-March 2013 (low precipitation), September-October 2013 (rainy season) and March 2014 (dry season). Multiple comparison of pairs of means using the DGC test. Means of 250 samples in each season. Identical letters denote non-significant differences ($P < 0.05$). Severities PC 0 and PC 1 included palms for the treatments T3, T4, T6 and T7; and severity PC 2 included palms for the control treatments = T2, T5 and T8 (Table 1).

Photosynthesis

The recovery of the palms with the different treatments was monitored using measurements of photosynthetic activity throughout the day. In the rainy season of 2013, the photosynthetic rate of the recovered palms (PC 0), reached 14 µmol CO_2 m^{-2} s^{-1} during most of the day, while the palms in recovery (PC 1) and palms with severe symptoms (PC 2) barely exceeded 7 µmol CO_2 m^2 s^{-1}. Transpiration of healthy palms was significantly higher than that for PC affected palms with both degrees of severity, which indicates intense physiological activity and high soil water extraction capacity (figs. 10 and 11). In the dry season of 2014, the greatest physiological activity occurred in the recovered palms (photosynthetic rate of 17 µmol CO_2 m^{-2} s^{-1}), while palms with PC symptoms reached a maximum of 13 µmol CO_2 m^{-2} s^{-1}(Fig. 11).

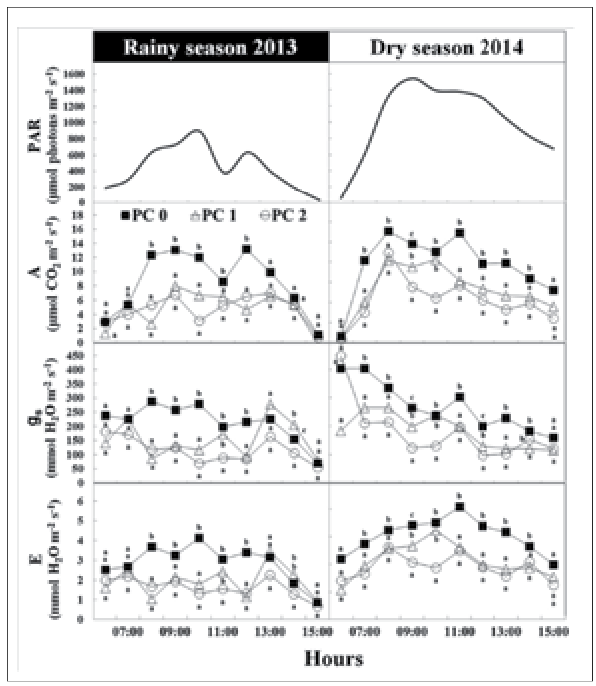

Fig. 11. Photosynthetically active radiation (PAR), net photosynthesis (A), stomatal conductance (g_s) and transpiration (E) of leaf No. 9 in the three categories of PC severity. Multiple comparison of pairs of means using the DGC test. Means of 24 samples per hour per severity in each season. Identical letters denote non-significant differences ($P < 0.05$). The severities PC 0 and PC 1 included palms for the treatments T3, T4, T6 and T7; and severity PC 2 included control palms = T2, T5 y T8. 'Dry season' simply denotes the less rainy period (Fig. 2).

Nutrients in the leaves

The palms recovered from PC showed optimum contents of macro and micronutrients. Their contents of N, Fe, S and K were higher than in the controls, but the contents of B and Ca were lower. In all the treatments, the Fe/Mn ratios were 1:2; indicating a possible imbalance.

Fruit and oil yield

The effectiveness of the recovery induced by the treatments and reflected in the higher photosynthetic activity, growth and recovery from PC symptoms, was also evident in fruit yield (complete treatment without ablation). Palms with initially advanced and severe symptoms produced 27 and 19 more kilograms of fruit bunches than the absolute control (P < 0.05). The increase was in the number of bunches, but not in their weight. The gain in oil production was estimated at one ton in the case of palms with initial advanced symptoms (PC 1) and at 1.4 tons for palms with severe symptoms (PC 2) (Table 3).

Table 3. Production of fresh fruit and oil versus initial PC severity (November 2012) and treatments for recovery. Means of 10 samples per treatment. Comparison of means using the *t*-test (P < 0.05)

PC	Treatment	Fruit production (kg palm^{-1}year^{-1})	Number of bunches (No. palm^{-1}year^{-1})	Bunch weight (kg)	Oil in bunch (%)	Oil/HA tons year^{-1}
1	T4	108.2	15.6	6.9	17.0	2.9
	T5	81.2	11.8	6.9	15.2	1.9
	difference between means	27.0*	3.8*	0.0 n.s.	1.8*	1.0*
2	T7	128.2	17.5	7.3	16.3	3.3
	T8	110.1	15.6	7.0	11.1	1.9
	difference between means	18.1 *	1.9*	0.3 n.s.	5.2*	1.4*

t-test;* = statistically significant differences and n.s. = non-significant differences.

Discussion and Conclusions

PC symptoms were initially observed in late 2012. This event was preceded by a prolonged period of rains that extended from May to November (average of 390 mm/month), followed by a significant reduction in rain from January to March 2013 (average of 35 mm/month). From May to November of the next year (2013), another prolonged period of high precipitation occurred (445 mm average/month), which was associated with a notable increase in the incidence and severity of PC. At this site, Torres et al (2014) found a relationship between PC and soil moisture saturation during La Niña years (deterioration of roots due to hypoxia), followed by El Niño years with abnormally dry seasons that further deteriorated the root system.

The pattern of the appearance of new PC cases was associated to a greater extent with variations in ground contour (discreet foci in depressions of the terrain) and with the deterioration of the physical properties of the soil; both factors had a negative effect on surface drainage during the rainy season. This situation caused an increment in the soil volumetric water content in the upper layers; which was associated with a significant reduction of root density and an increase in the severity of the symptoms. Surface drainage was also limited due to soil compaction and the loss of structure in the Ap horizon due to the intensive tilling that these soils suffered in the past.

As a result of the stress suffered, an abnormal behavior was observed in the physiology of the PC affected palms. In the dry season of 2013, the affected palms showed a transitory increase in stomatal conductance and leaf temperature, but with their reduced root density, the capacity to absorb soil water and minerals in sufficient quantities was diminished. Eventually, a water and energy imbalance was generated that was manifested in the rainy season of 2013, when the PC symptoms were most severe, significantly diminishing photosynthesis, stomata conductance and transpiration of palms with severe symptoms, particularly in the lower areas of the plot, where the water table reached the root zone. All this may affect the chemical signals generated by the roots (Davies & Zhang 1991; Rajagopal et al. 1986).

In the 'dry' season of 2014, palms with PC symptoms showed less capacity to regulate water potential of the leaves and they were incapable of responding to the elevated evaporative demand of the atmosphere, probably as a mechanism to prevent the excessive loss of water during photosynthesis, which diminished significantly (Chinchilla & Durán 1999). Similarly, Moreno et al (2013) documented that the different stages of PC development significantly affected photosynthesis, stomata conductance, transpiration, and the metabolism of the oil palm.

The application of the recovery treatments was associated with the progressive reduction of the severity of aerial symptoms, and many palms appeared to be healthy after 18 months, which is not the norm in a susceptible clone like the one studied. Recovery was preceded by an increase in root density, which made the recovery of stomata control possible, increasing the water potential of the leaves and photosynthetic activity, increasing vegetative growth, bunch production, oil accumulation and tolerance to biotic and abiotic stress.

Soil remediation improved the physical, chemical and microbiological properties of the soil, achieving a more rapid recovery of the root system. The improvement of surface drainage in the circle around the palm and the application of compost made a favorable environment for root growth (Bever et al. 2012, Mohammad et al. 2012, Mangan et al. 2010). The beneficial effect of the organic matter on the regeneration of the root system of palms affected by PC had been observed by Albertazzi et al. (2009b). In soil that was not treated with compost, there was a prevalence of potentially pathogenic microorganisms that appeared to have greater tolerance to anaerobiosis.

The poor surface drainage at the site was corrected by excavating surface drainage waterways specifically designed for the irregularities of the terrain around each palm. This made possible the rapid evacuation of surface water toward the quaternary network of canals, such that during the rainiest months of 2014 (400 mm/month), the soil volumetric water content at the site remained near 33%.

There was little difference in root density between treatments where inflorescences were removed or not. These data, and the fact that the differences in severity were not very notable with or without ablation, appear to indicate that this practice was not determinant in assisting root development or PC recovery. In addition, the differences in severity between treatments T1 and T2, which did not include ablation, did not show notable differences in severity when the disorder appeared in these initially healthy palms. Nevertheless, aerial vegetative growth was indeed greater with ablation of the inflorescences, especially the increase in trunk height.

The partition of assimilates occurs between antagonistic but complementary processes: vegetative growth, reproductive development, the storage of reserves, and defense activities. Modern varieties of palms are precocious, with high fruit and oil yields; therefore they can be highly susceptible to environmental stresses because they have sacrificed the assignment of resources to vegetative growth and to defense in order to increase oil yield.

Ablation is a little explored agricultural practice in oil palm (Corley & Breure 1992; Legros et al. 2009). The removal of inflorescences and bunches in development is an attempt to modify the distribution pattern of the assimilates and divert them to vegetative growth, which effectively occurred in the clone with respect to the aerial part. However, the benefits regarding root development were not clear. Palms store large quantities of reserve substances in the trunk for the purpose of buffering photosynthetic deficiencies of the crown under unfavorable climatic conditions, but rapid transport of these substances toward the roots might not occur (Basri et al. 2004; Legros et al. 2009; Milaet-Serra et al. 2006).

We conclude that the application of a soil remediation treatment, together with agrochemicals on the foliage did not impede the development of symptoms in plants with an initial healthy appearance (according to the initial evaluation in November 2012), nor did they appear to reduce the period necessary for a natural recovery (which occurred after a variable period). However, the severity of the symptoms was less in the treated plants.

The early removal of necrotic tissue from the petiole bases had an effect on the recovery of palms with PC, since it prolonged the longevity of the leaf tissue, which otherwise would have died prematurely with the breakage of the leaf in the petiole area.

Palms that did not fully recover from PC symptoms during the evaluation period (controls) showed a significant reduction in fruit and oil yields. The increase in the number of bunches on treated palms could have been due to a lower percentage of abortion and/or failure thereof. The reduction in oil content in the fruits of the control could have been related to the interruption of the oil synthesis process and the reduction of the number of fertile fruits in the bunch (Chinchilla & Durán 1999).

Due to the difficulty of carrying out some of the soil remediation treatments for individual palms in some situations (for example, where there is extensive deterioration in the entire palm crop area (making suitable drainage for individual palms impossible)), their execution might not be feasible unless the improvement practice is done previously for the whole plantation. On the other hand, if the problem is allowed to expand and the number of plants to be treated augments considerably, it might not be feasible to give 'personalized' attention to each affected palm. In addition, it could be argued that the cost of such detailed work on each palm could not be sound from an economical point of view.

In addition, we recognize that it is not possible to separate the effects of each practice carried out. In particular, the effect of each agrochemical applied to the foliage or the soil cannot be distinguished, and it is possible that the large amount of fertilizer added to the soil would create eventually significant imbalances among various nutrients, with possible undesirable consequences. Therefore, these details must still be clarified. Nevertheless, the initial proposed objective intended to demonstrate that it is possible to reduce symptom severity and eventually accelerate the recovery of a PC affected palm, even in the case of a highly susceptible clone with a long natural recovery period, through agronomic improvement of the soil properties to allow better root development, which was documented in this study. We conclude that in order to achieve recovery from PC symptoms, first the oil palm root system must be regenerated, to allow subsequent recovery of vegetative aerial growth and finally, an increase in oil and bunch production.

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