FIVE YEARS (2018-2022) MONITORING OF PLANT RECRUITMENT ON MOTU REIONO, TETI'AROA ATOLL (SOCIETY ISLANDS) : EFFECTS OF RAT ERADICATION AND NATURAL DISTURBANCES

by

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Background and objectives

The goal of this study was to conduct a multi-years monitoring of plant recruitment (mainly seedlings of woody native and alien species) in permanent transects and quadrats set up in the atoll of Teti'aroa before and after a rat eradication operation (SAMANIEGO *et al.* 2020) in order to better understand forest dynamics during this ecological restoration project, and to try predict the ecosystem successional trajectory. This long-term monitoring provided also an opportunity to assess changes in plant recruitment after natural disturbances (especially tree falls, high tides and strong swells) that occured during the study period.

Material and methods

Study site

Motu Reiono (ca. 22 ha) is the southernmost « motu » (sandy islet in Polynesian language) of the coral atoll of Teti'aroa located in the Society Islands, French Polynesia (**Fig. 1**). It was inhabited in ancient times by Polynesians, as evidenced by the presence of several archeological structures, including a temple (« marae Apara »), meeting houses (« fare pote'e ») and an archery platform (MOLLE *et al.* 2019). The motu was then temporary occupied during the European period with a coconut trees plantation set up in the 1950's (according to aerial photographs). The current vegetation is relatively intact with a the vascular flora composed of 15 native species and five naturalized alien plants including *Cocos nucifera* and Polynesian introduced trees such as *Morinda citrifolia* (« noni »), *Barringtonia asiatica* (« hotu »), *Talipariti tiliaceum* (syn. *Hibiscus tiliaceus*, « purau ») and *Thespesia populnea* (« miro ») (MEYER 2018).

Figure 1. Satellite image of Motu Reiono (Pleiades 2014, © IDEA-ETH Zurich) with the location of the 10 study plots (courtesy of Benoît STOLL, Université de la Polynésie française).

Permanent transects, quadrats, and circular plots

An experimental protocol, inspired by a similar study (WOLF *et al.* 2018) conducted in the ca. 230 ha uninhabited atoll of Palmyra in the Northern Line Islands (North Pacific) during a previous rat eradication project, was used in Reiono: we set up 25 m long x 2 m large transects (*i.e.* a total area of 50 m²), marked on its median line and at both ends by iron posts, tagged with color flags indicating the transect number (TR1 to TR10). Each transect was divided into fifty 1 x 1 m quadrats located on both side (right and left) of the median line (**Fig. 2**). The « start post » and « end post » were georeferenced with a GPS (Garmin Map 64s) and direction from start post to end post was assessed with a compass.

In each of the 50 quadrats, the total number of seedlings (< 30 cm in height) was counted for each woody plant species, as well as coconut « seedlings » (*i.e.* germinating coconuts with 1 to 6 small leaves). Resprouts (*i.e.* small stems with leaves) from roots were not counted, as well as coconuts without any leaves (*i.e.* young and full of water, or opened and empty, or dried and dead).

A total of 10 transect was set up in the interior of the motu (**Fig. 1**), representing a sampled area of 500 m², in different forest types. Transects were not selected in plant habitats located at the periphery of the motu, such as dense shrublands of *Scaevola taccada* (« naupata » in Tahitian language or beach cabbage in English) and *Suriana maritima* (« ‘o’uru » or bay cedar) and low canopy forest of *Heliotropium arboreum* (syn. *H. foertherianum,* « tāhinu », « tōhinu » or tree heliotrope) to avoid both forest edge effects and the impacts of seawater on seedling survival. We have also avoided *Pisonia grandis* (« pu’atea » or cabbage tree) forests with an understorey dominated by the large terrestrial fern *Asplenium nidus* (« 'ō'aha » or bird’s nest fern) where it was too difficult to set up quadrats.

In order to better characterize the different plant habitats/forest types, we have set up 25 m diameter circular plots (CR1 to CR10) centered around the transects (*i.e.* with an area of about 490 m²). The total sampled area of 4900 m² (0.49 ha) represents about 2% of the land surface of Motu Reiono (**Fig. 2**). The number of standing trees and their number of trunks and stems with a diameter at breast height (DBH, taken at 1,30 m from the ground) above 10 cm were counted and their diameter (or circonference) measured. The total basal area (BA in cm²/m² or m²/ha) for each species based on the surface (s) of all its individuals (i), and for all species were calculated as followed:

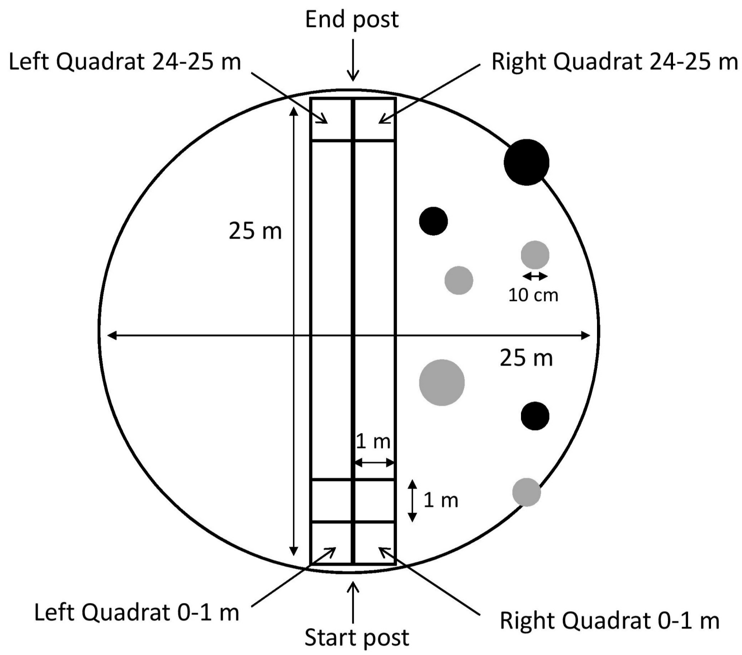
$$s = \frac{\pi \times DBH^2}{4} \qquad BA = \frac{\sum_i s_i}{490}$$

The percentage of basal area for each species (%BA) was assessed to identify the dominant species in relation to their cover.

Monitoring dates and period of survey

We started our study in July 2018, one month before the rat eradication campaign of August 2018 (SAMANIEGO *et al.* 2020) until July 2022, representing a five years monitoring period. Post-eradication surveys were conducted in June, July or August during the dry and cool season in the Society Islands in order to avoid seasonal variability in seed germination and seedling recruitment caused by heavy rains during the warm and rainy season (between November and March). Due to the covid-19 sanitary crisis that hit French Polynesia in the mid-2020, no field trip was organized between June and July, but we were able to collect some data in January 2020 when we set up the circular plots and measured tree species basal areas, and a few more in August 2020 (DEFILLION 2020).

<u>Figure 2.</u> Diagram showing the circular plots (CP) centered in the middle of the permanent transect (TR).



Results

A total of 323 trees (representing 417 trunks and stems) were counted and their diameter measured in the 10 circular plots, representing a total basal area of 662 cm²/m². The density reaches about 660 trees/ha in the sampled area (**<u>Tab. 1</u>**). The two most common trees are *Pisonia* and *Cocos*, followed by *Guettarda speciosa* (« tafano ») and *Pandanus tectorius* (« fara »), with few *Heliotropium arboreum*. It is notheworthy that the abundance of *Pandanus* seemed to be underestimated using the BA method because of its more slender trunks.

<u>Table 1.</u> Forest composition and woody species cover in the circular plots according to the number of trees and stems (DBH > 10 cm) and Basal Area (cm²/m² or m²/ha). Piso.= *Pisonia grandis*; Coco. = *Cocos nucifera*; Pand. = *Pandanus tectorius*; Guet. = *Guettarda speciosa*; Helio. = *Heliotropium arboreum*.

Circular plot	Number of trees	Number of stems	Total Basal Area	BA Piso.	BA Coco.	BA Pand.	BA Guet.	BA Helio.
CP1	23	38	70,65	68,96	1,69	0	0	0
CP2	28	38	94,50	80,44	14,06	0	0	0
CP3	30	40	59,64	57,23	2,42	0	0	0
CP4	31	32	64,72	19,35	45,36	0	0	0
CP5	40	50	41,04	23,74	3,66	3,78	3,45	6,42
CP6	43	50	100,50	91,72	8,78	0	0	0
CP7	33	45	73,90	62,16	9,14	0	2,60	0
CP8	31	43	32,83	18,70	4,63	5,43	4,08	0
CP9	31	40	47,73	39,32	6,21	0	2,20	0
CP10	33	41	76,67	42,74	33,93	0	0	0
Total	**323**	**417**	**662,18**	**504,36**	**129,88**	**9,21**	**12,33**	**6,42**
Density/ha	659	851	-	-	-	-	-	-

In Palmyra atoll, only three types of forests were recognized according to the coconut tree cover based on adult basal area: « *High Cocos* » (>75% of the total basal area), « *Low Cocos* » (<25%) et « *Intermediate Cocos* » (between 25-75%) (YOUNG *et al.* 2010, WOLF *et al.* 2018). We used a forest classification based on the %BA for each woody plant taxa (**Tab. 2**) allowing us to describe the different forest types in a more quantitative and detailed way than visually (*e.g.* MEYER 2018). Results indicate that there were only two replicates for the « *Pisonia* dense forest with *Cocos* very rare » (TR1 and TR3) and the « *Pisonia* dense forest with *Cocos* uncommon » (TR2 and TR7) forest types, the six other plots being different in their composition and tree cover (**Tab. 3**).

Table 2: Forest classication according to the % basal area of each taxa with main types.

Forest type	%BA of taxa
Forest dominated by X (« *X dense forest* »)	X>75%
Forest codominated by X and Y (« *X-Y dense forest* »)	30%<X<75% and 30%<Y<75% and X-Y<10%
Mixed forest dominated by X (« *Mixed X forest* »)	30%<X<75% and X> all other taxa
Mixed forest dominated by X with Y (« *Mixed X forest with Y* »)	Y>25% and X-Y>10%
With Z uncommon	10%<Z<25%
With V rare	5%<V<10%
With W very rare	W < 5%

Table 3. Description of the different habitat/forest types based on forest classification.

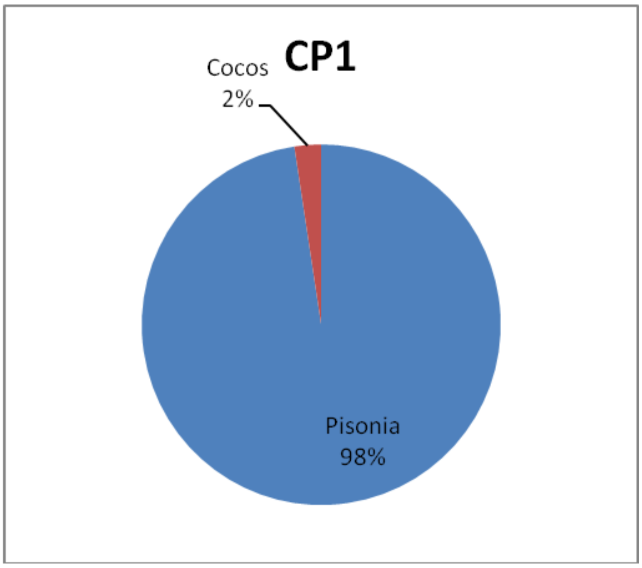
Plot/Transect	Habitat/forest type
CP1/TR1	*Pisonia* dense forest with *Cocos* very rare
CP2/TR2	*Pisonia* dense forest with *Cocos* uncommon
CP3/TR3	*Pisonia* dense forest with *Cocos* very rare
CP4/TR4	Mixed *Cocos* with *Pisonia*
CP5/TR5	Mixed *Pisonia* forest with *Heliotropium* uncommon and *Pandanus, Cocos, Guettarda* rare
CP6/TR6	*Pisonia* dense forest with *Cocos* rare
CP7/TR7	*Pisonia* dense forest with *Cocos* uncommon
CP8/TR8	Mixed *Pisonia* forest with *Pandanus, Cocos, Guettarda* uncommon
CP9/TR9	*Pisonia* forest with *Cocos* uncommon and *Guettarda* rare
CP10/TR10	*Pisonia-Cocos* dense forest

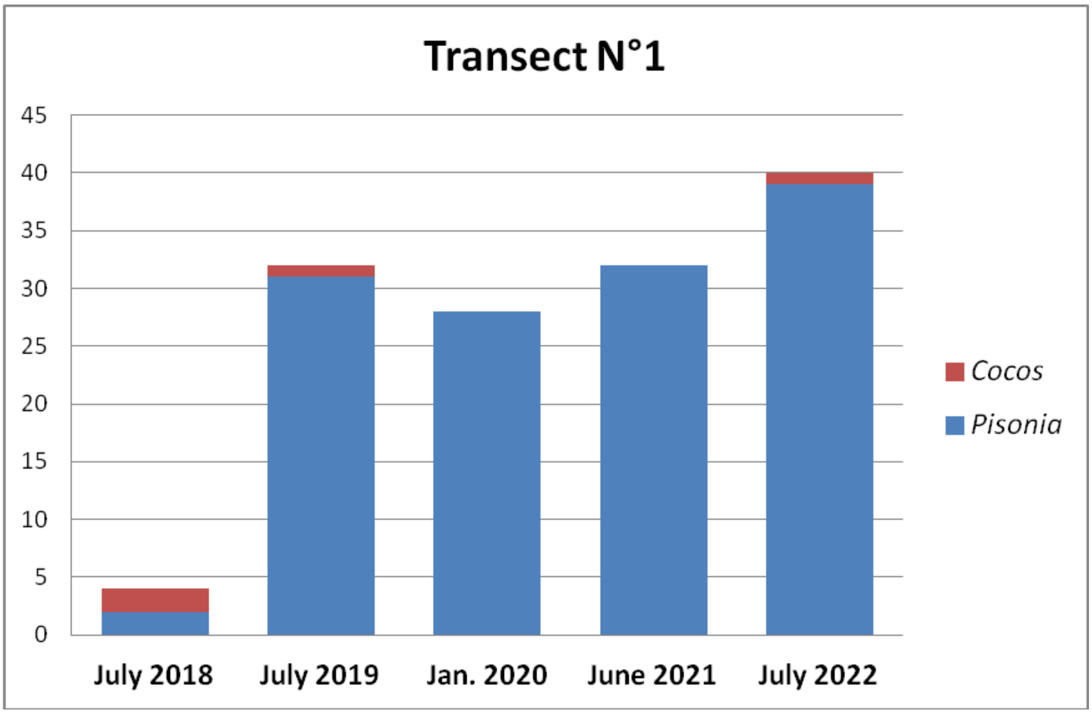
During the study period (2018-2022), seedlings of four woody species were recorded in the quadrats and transects (**Fig. 3-12**): the introduced *Cocos nucifera* and the native trees *Pisonia grandis*, *Pandanus tectorius*, *Guettarda speciosa*. We have also counted seedlings of the native climbing woody vine *Ipomoea violacea* (syn. *I. macrantha*, « pōhue tātahi ») in three transects (TR5, TR8 and TR9). No seedling of the tree *Heliotropium arboreum* was observed in the ten transects during the study period.

As expected, seedling recruitment differs according to forest types, with more *Cocos* seedlings found in mixed *Cocos* forest, more *Pisonia* seedlings in dense or mixed *Pisonia* forest, and *Pandanus* seedlings only in mixed forest with *Pandanus*. An increase of *Pisonia* seedling was observed in *Pisonia* dense forests before and after rat eradication (TR1, TR2, TR3, TR6 and TR7, see **Photos** in **APPENDIX**), as well as *Cocos* seedlings in mixed *Cocos-Pisonia* forests (TR4 and TR10, see **Photos**). The dramatic increase in *Pisonia* seedlings observed in TR7 (raising from about 380 in 2018 to more than 1050 in 2019) can be explained by a tree fall gap near the transect (see **Photos**), and the sudden decrease in TR5 and TR8, both located on the southern tip of Motu Reiono, by coastal flooding caused by the passage of a high tide or a strong swell in 2020 and 2021 respectively (see **Photos**).

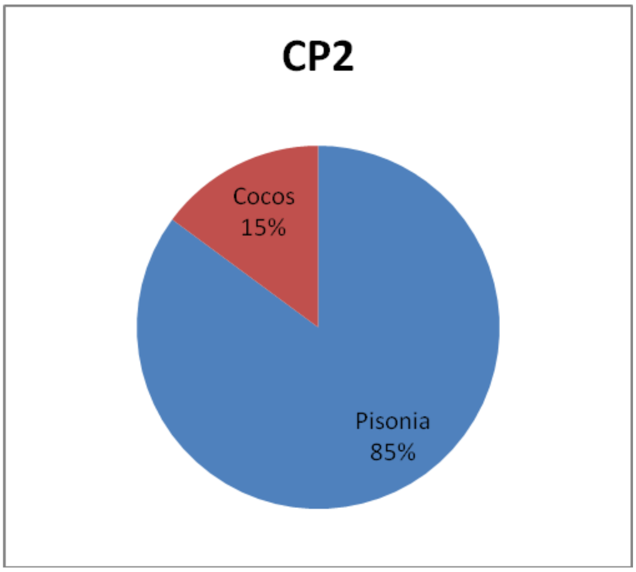
A new burst of *Pisonia* seedlings was observed in TR5, TR8 and TR9 after an episode of strong swell in mid-July 2022. Few *Guettarda* seedlings appeared lately in 2020 and 2021 in one mixed forest with many *Guettarda* trees (TR8), but none were observed in the other transects with some *Guettarda* trees (TR5 and TR9).

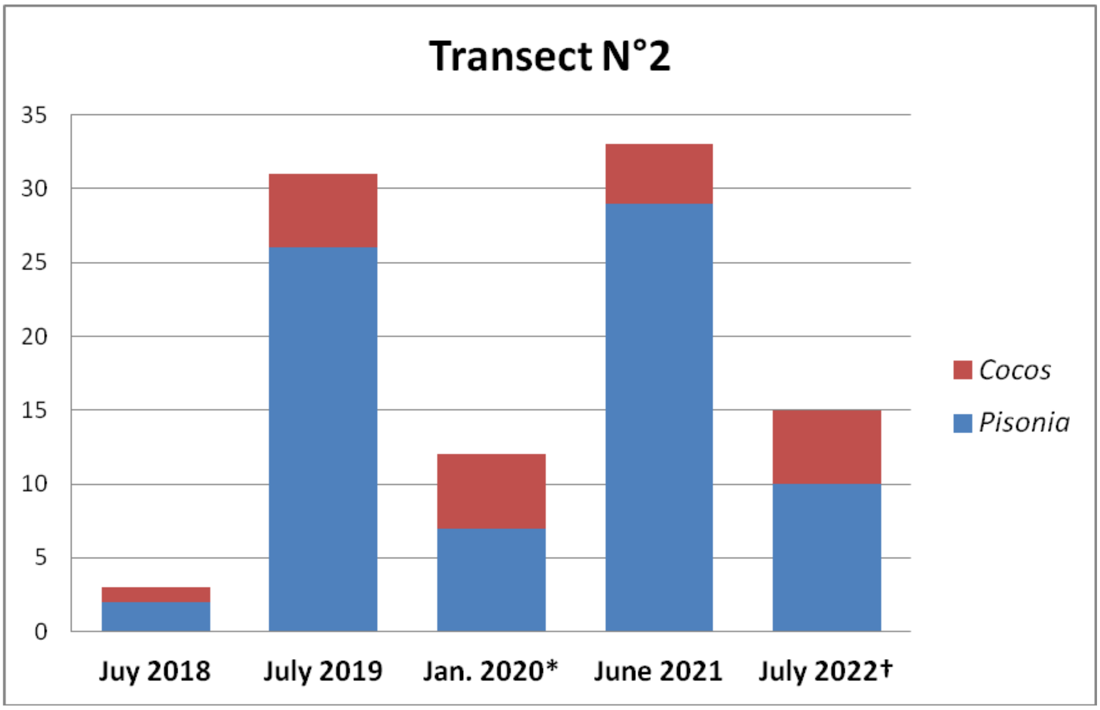
<u>Figure 3.</u> Forest composition and woody species cover (%BA) in circular plot CP1, and evolution of the seedlings number in permanent transect TR1 between 2018 and 2022.



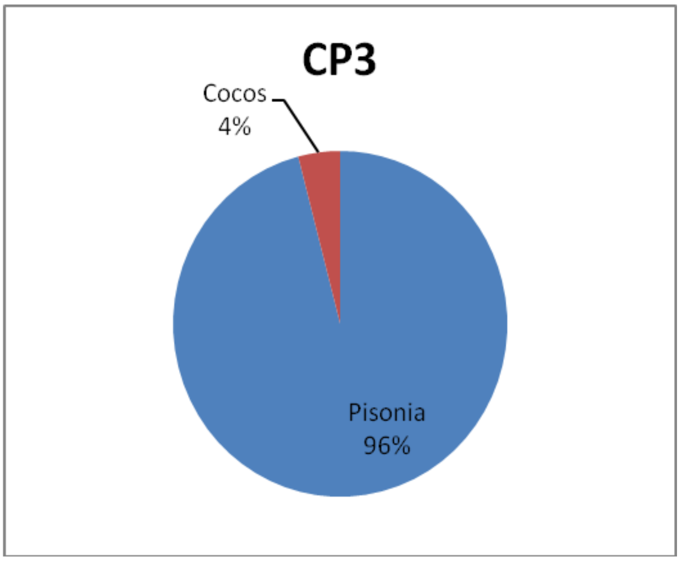


<u>Figure 4.</u> Forest composition and woody species cover (%BA) in circular plot CP2 (near the shore, east side), and evolution of the seedlings number in the permanent transect TR2 between 2018 and 2022. *Many broken branches found on the ground probably related to strong winds.† Impacts of the strong swell of mid-July 2022.





<u>Figure 5.</u> Forest composition and woody species cover (%BA) in circular plot CP3, and evolution of the seedlings number in the permanent transect TR3 between 2018 and 2022. # Signs of a flooding (muddy soil) and high crab activity.



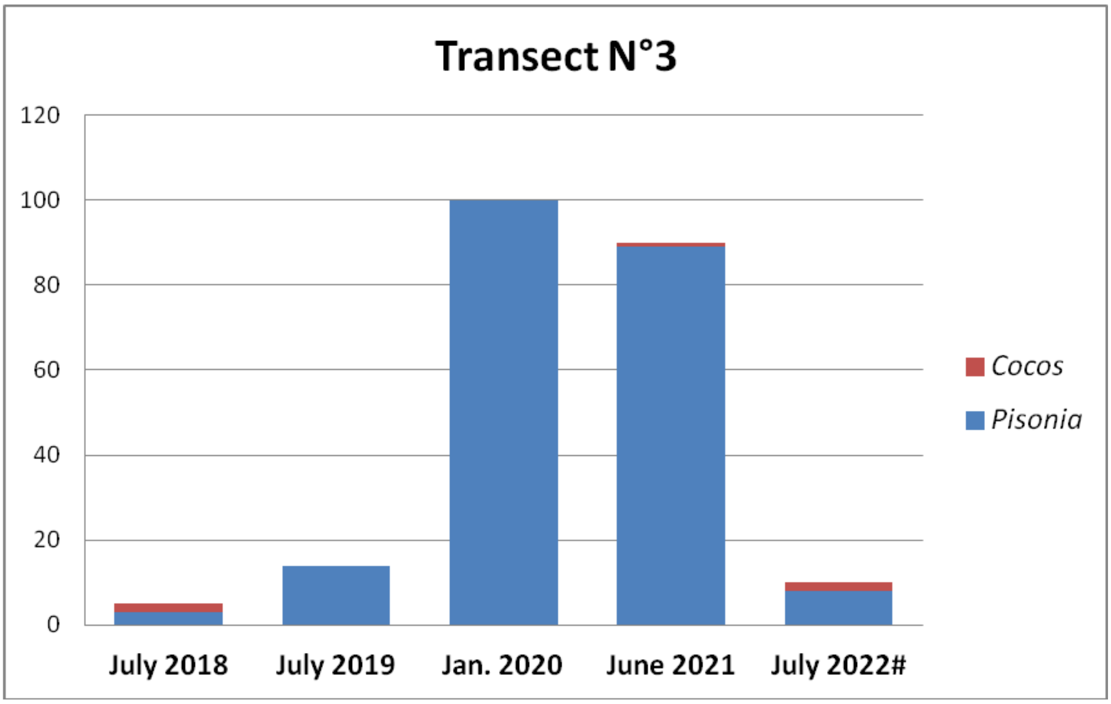
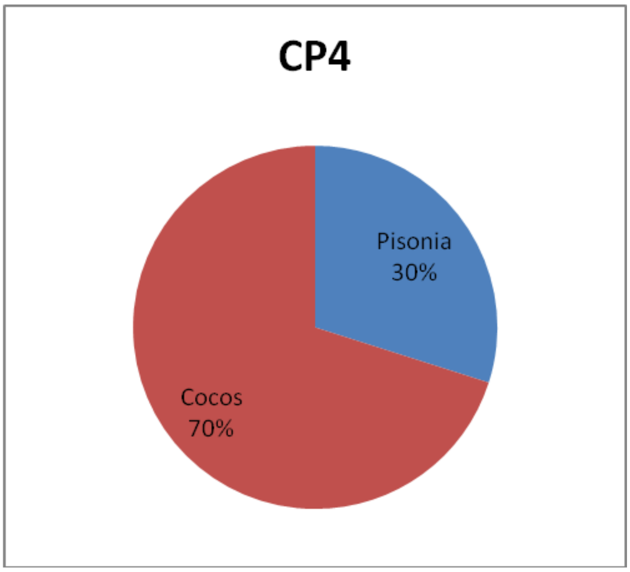
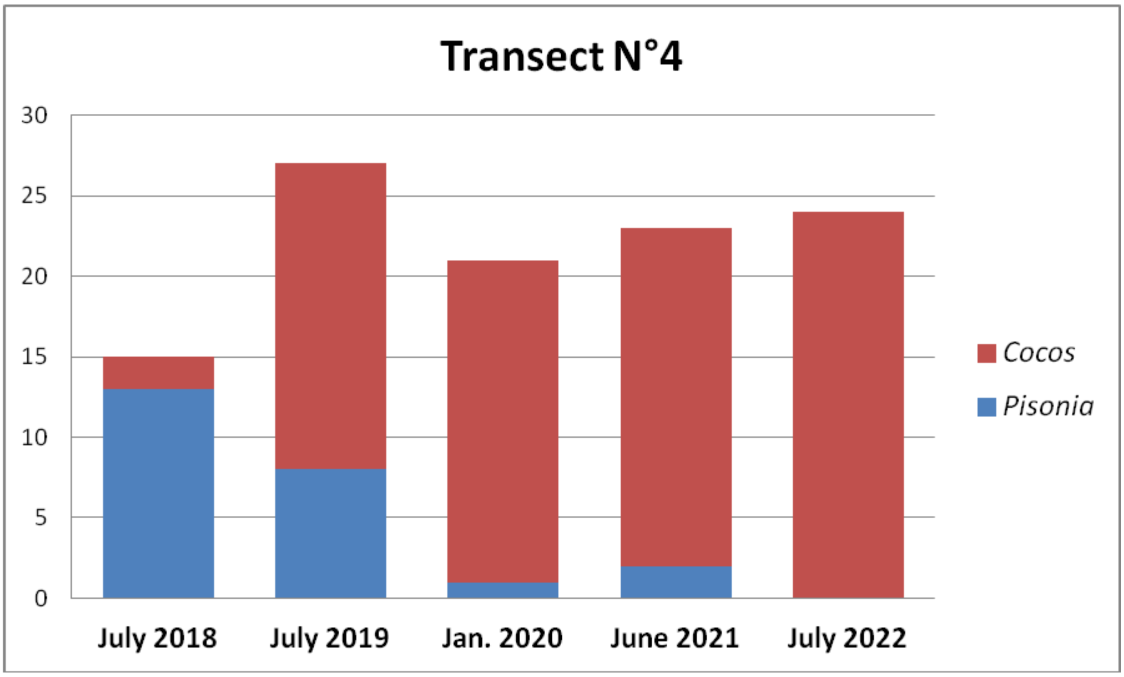
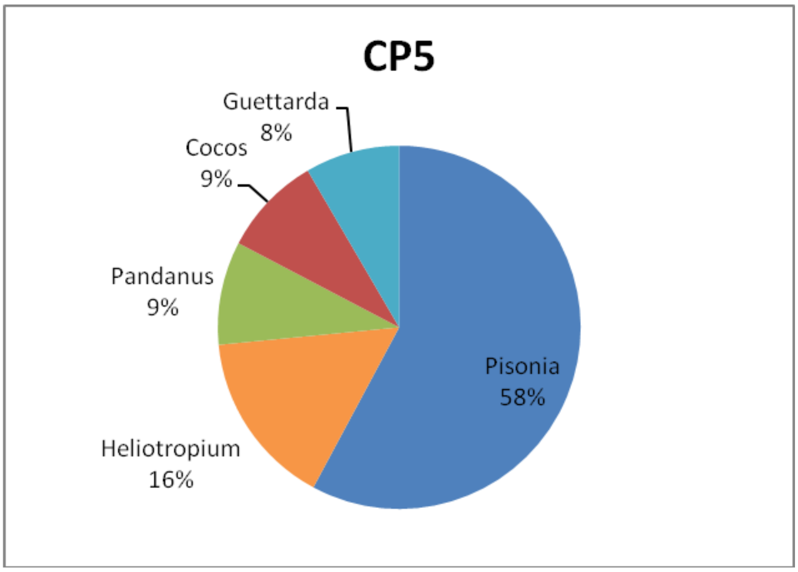


Figure 6. Forest composition and woody species cover (%BA) in circular plot CP4, and evolution of the seedlings number in the permanent transect TR4 between 2018 and 2022.





<u>Figure 7.</u> Forest composition and woody species cover (%BA) in circular plot CP5 (near the shore, south side), and evolution of the seedlings number in the permanent transect TR5 between 2018 and 2022. ‡Passage of a high tide or strong swell on the transect. † Impacts of the strong swell of mid-July 2022.



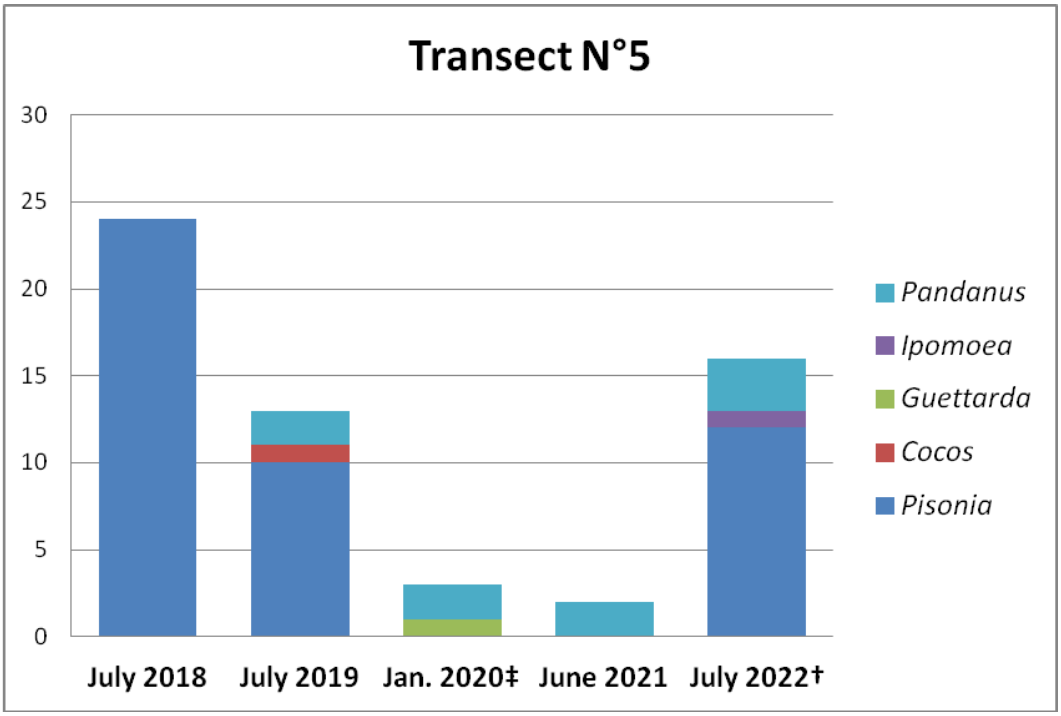
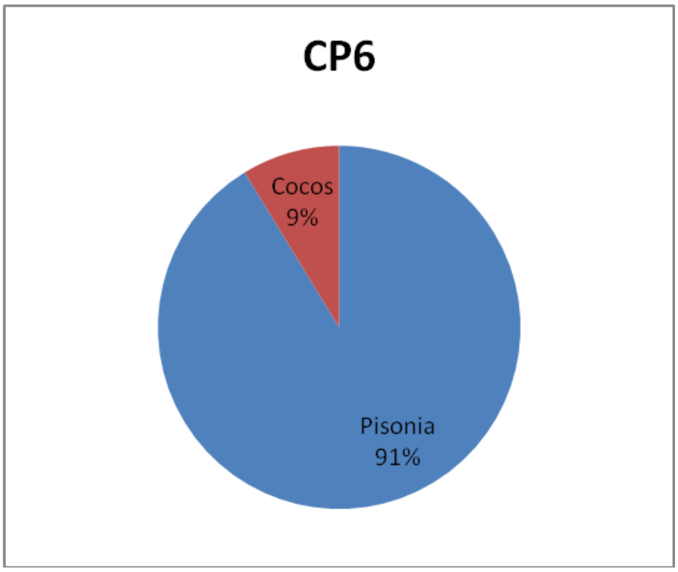
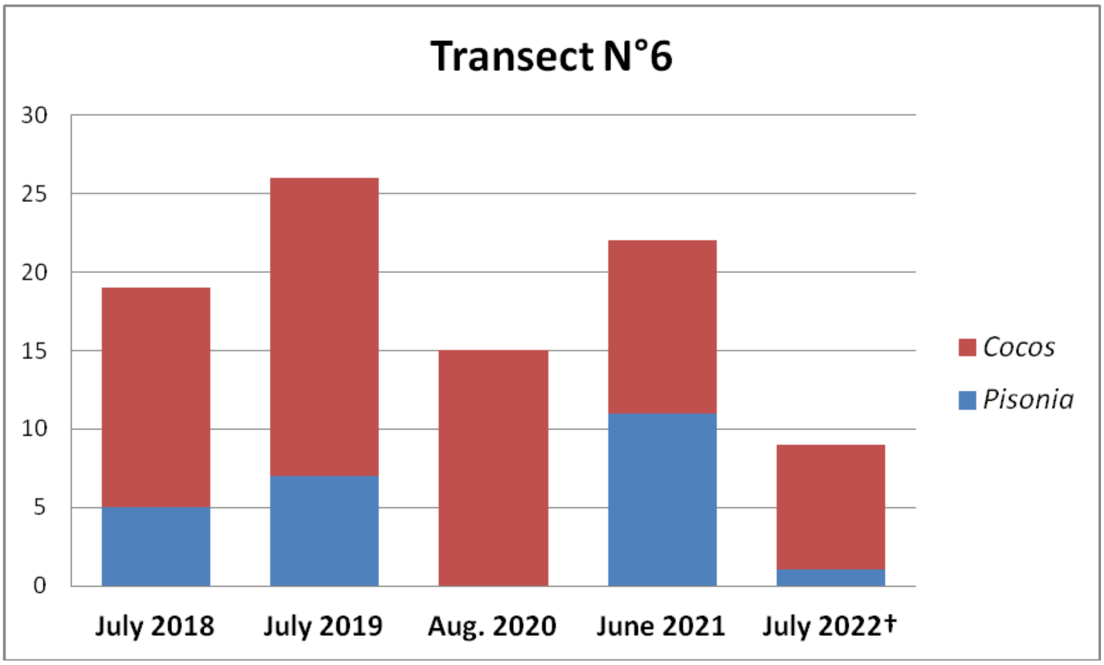
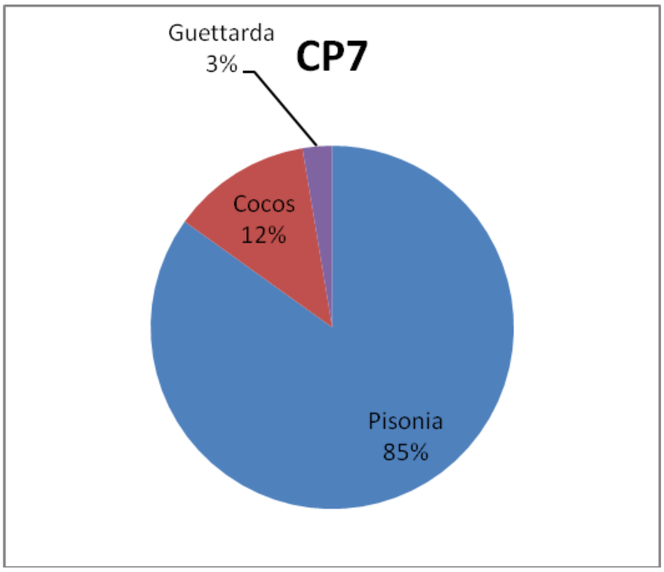


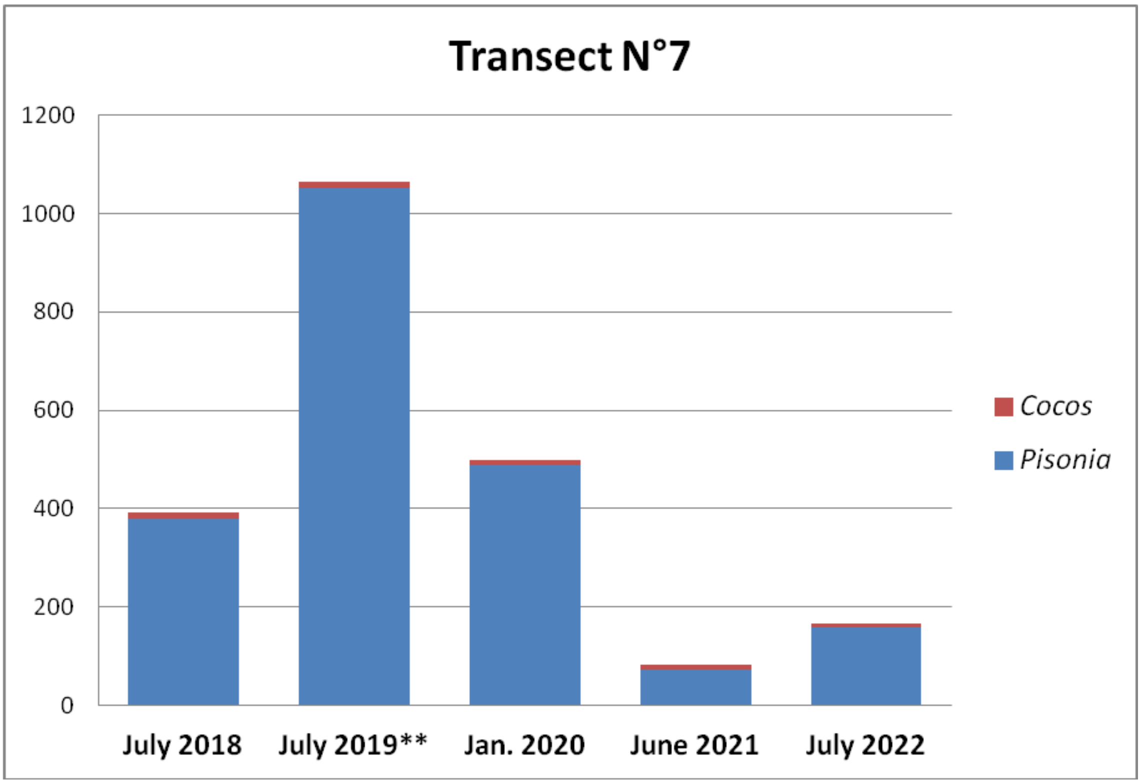
Figure 8. **Forest composition and woody species cover (%BA) in circular plot CP6 (near the shore, west side), and evolution of the seedlings number in the permanent transect TR6 between 2018 and 2022.** † Impacts of the strong swell of mid-July 2022.



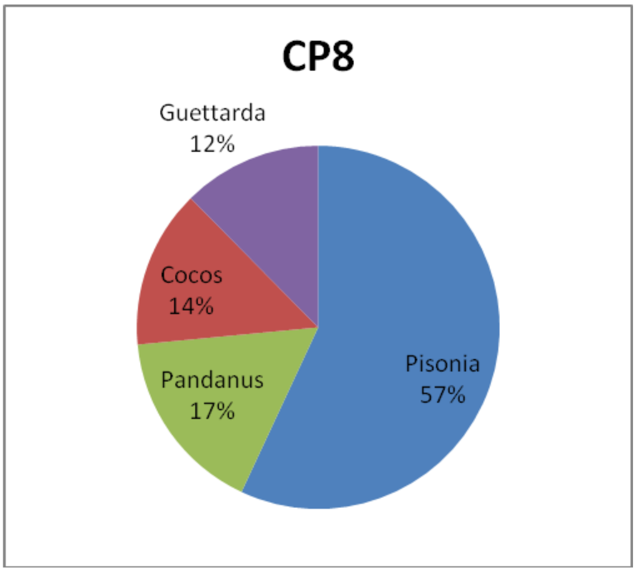


<u>Figure 9.</u> Forest composition and woody species cover (%BA) in circular plot CP7, and evolution of the seedlings number in the permanent transect TR7 between 2018 and 2022. **Treefall gap (a fallen *Pisonia* tree nearby the transect).





<u>Figure 10.</u> Forest composition and woody species cover (%BA) in circular plot CP8, and evolution of the seedlings number in the permanent transect TR8 between 2018 and 2022.** ‡Passage of a high tide or strong swell on the transect. † Impact of the strong swell of mid-July 2022.



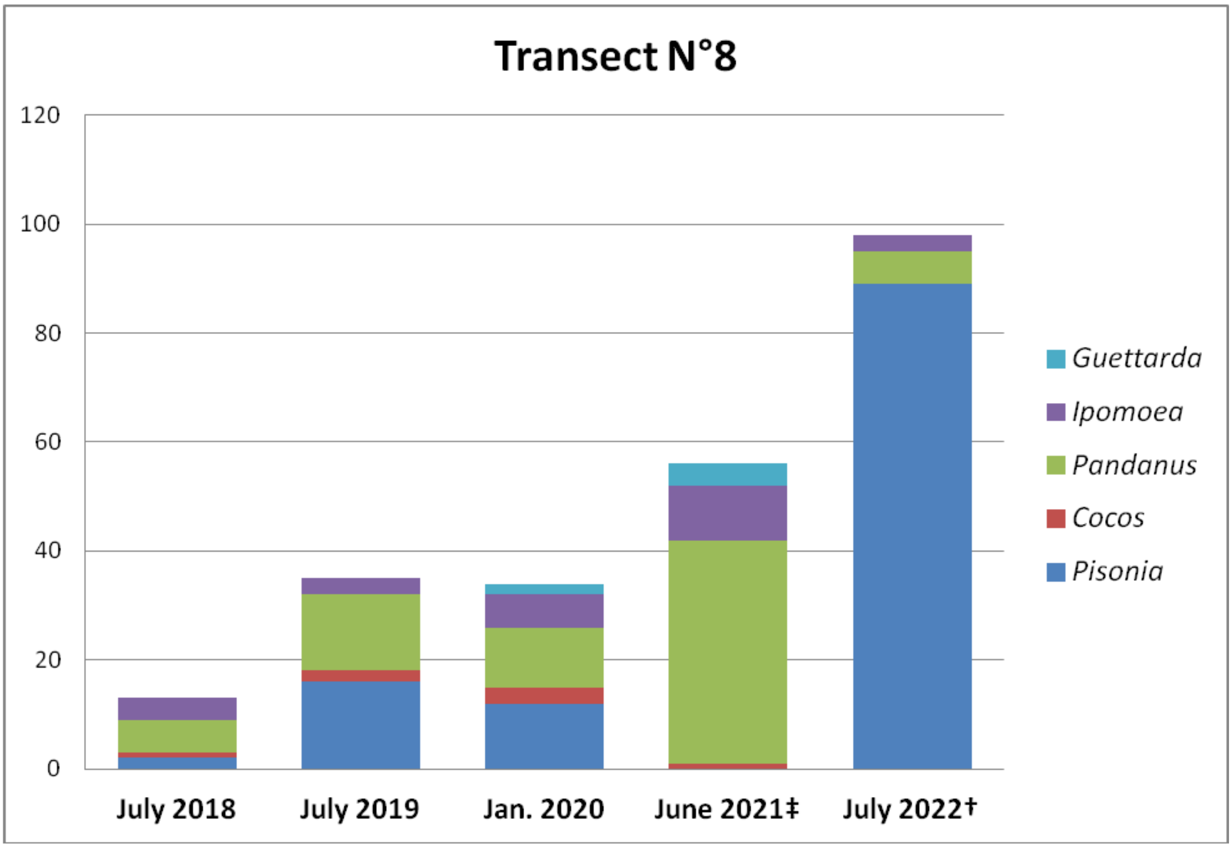
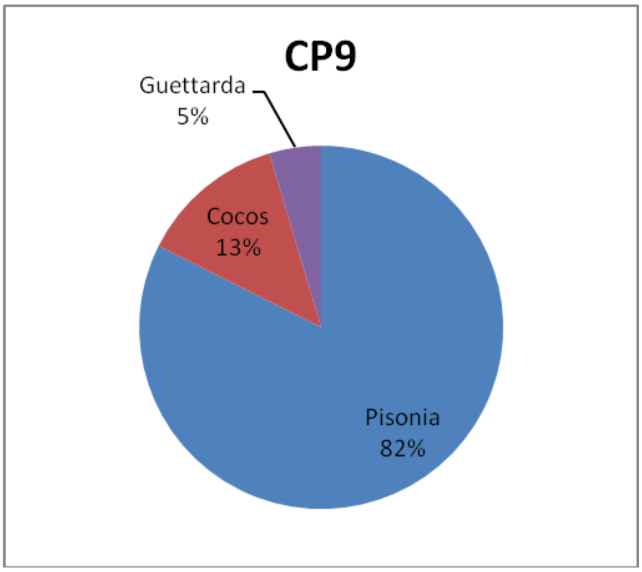
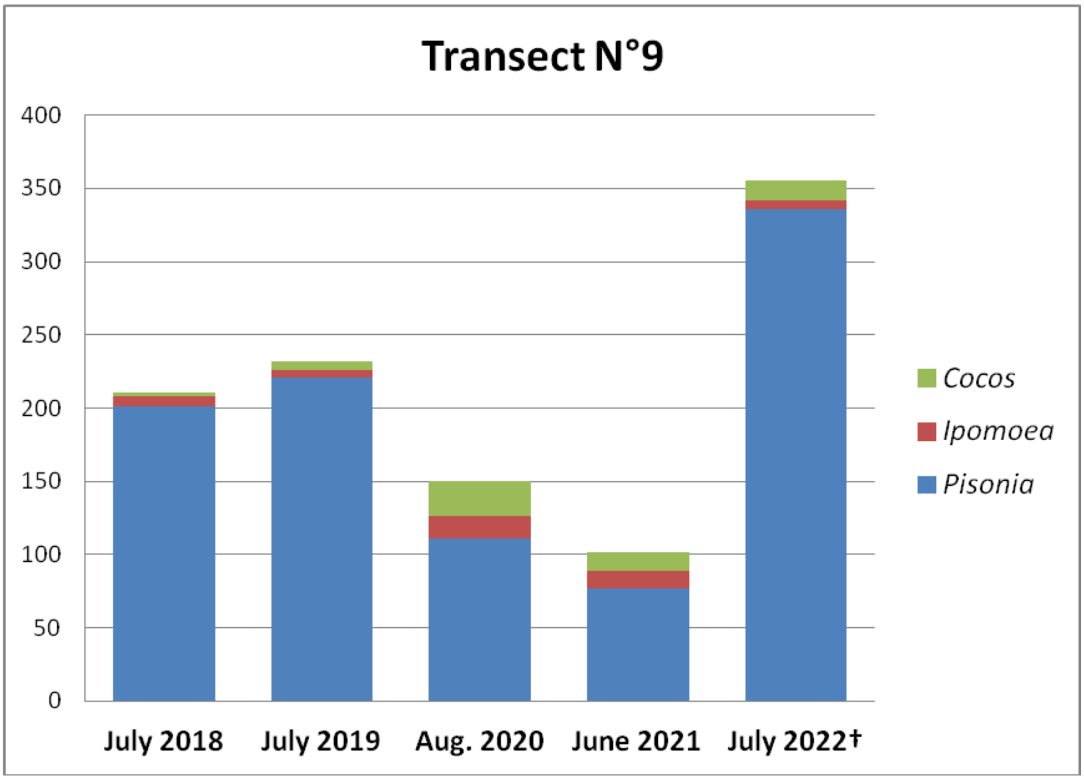
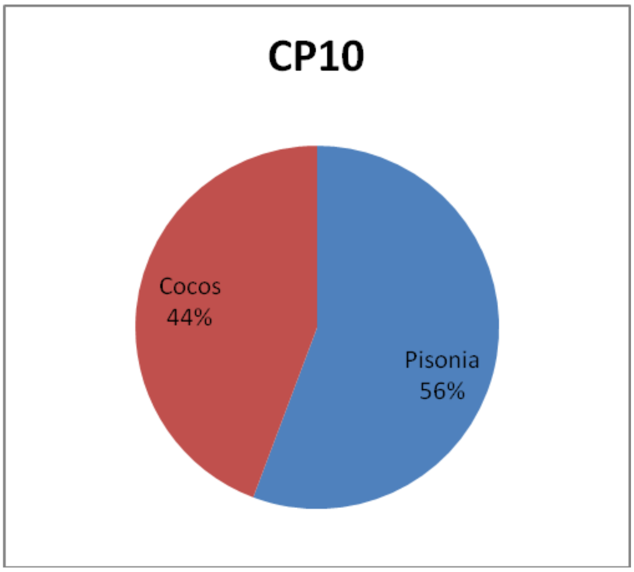


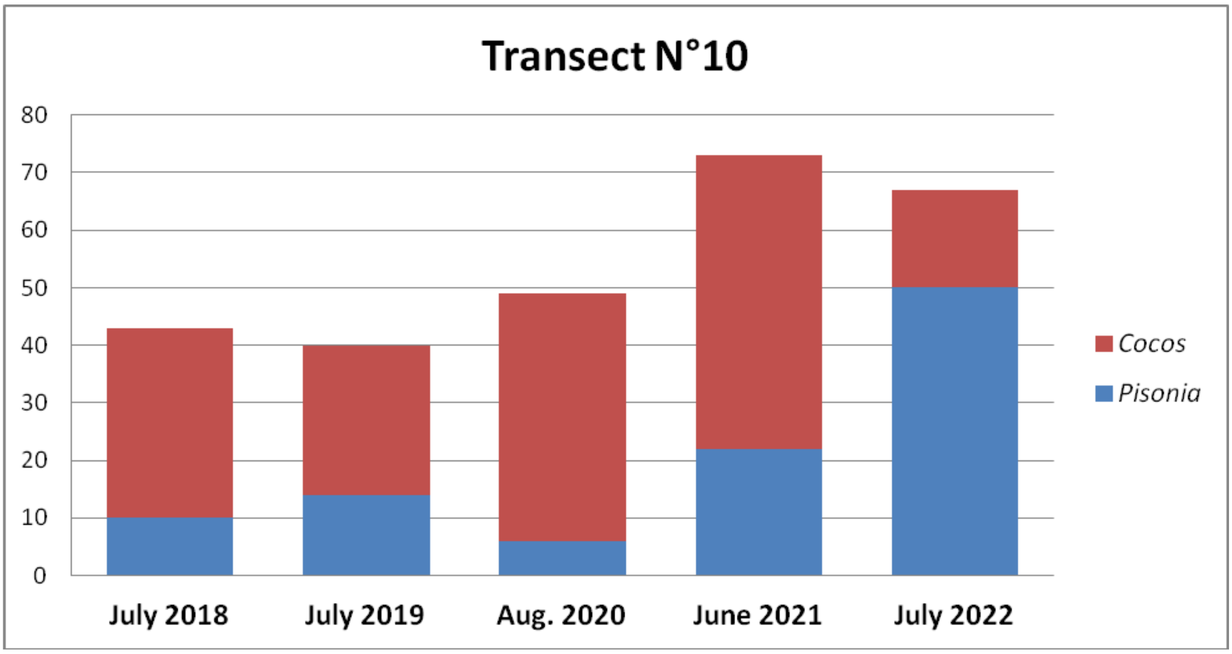
Figure 11. Forest composition and woody species cover (%BA) in circular plot CP9, and evolution of the seedlings number in the permanent transect TR9 between 2018 and 2022. † Impact of the strong swell of mid-July 2022.





<u>Figure 12.</u> Forest composition and woody species cover (%BA) in circular plot CP10, and evolution of the seedlings number in the permanent transect TR10 between 2018 and 2022.



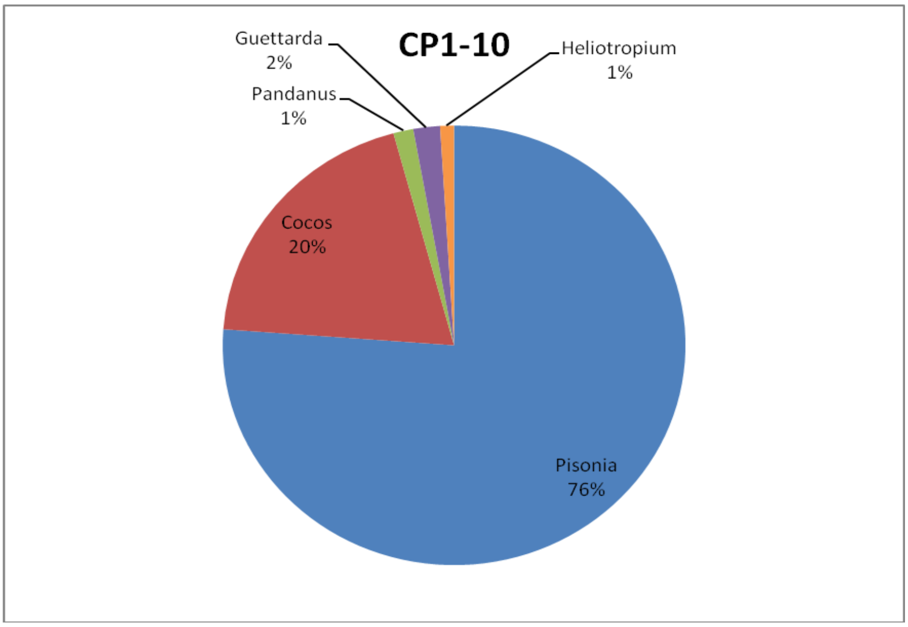


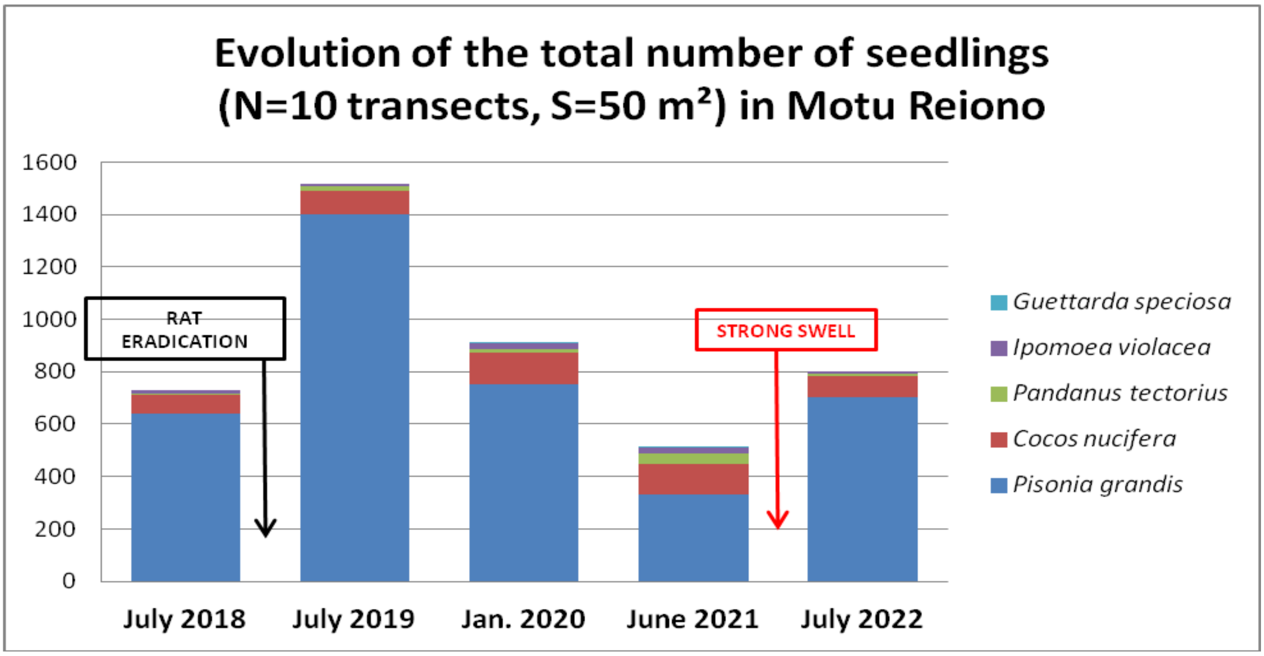
Conclusions and future prospects

Long-term monitoring by setting up permanent study plots is essential to study forest dynamics and understand ecosystem successional trajectories, especially after natural or anthropogenic disturbances, but also during ecological restoration efforts (e.g. weeding, herbivore exclusion, predator control).

The 10 permanent transects installed on Motu Reiono in well-described forest types allowed us to monitor (mostly woody native) plant species recruitment at a fine scale (number of seedlings per m²) before and after a rat eradication program over a four year period of time in a comprehensive way. As previously documented in the vegetation study conducted after rat eradication in Palmyra atoll (WOLF *et al*., 2018), we observed a seedling increase of the native tree *Pisonia grandis*, but also *Pandanus tectorius* and *Guettarda speciosa* which fruits, seeds and/or seedlings are presumably eaten by rats.

<u>Figure 13.</u> Forest composition and woody species cover (%BA) in circular plots (CP1-10) and evolution of the seedling number in the 10 permanent transects (TR1-10) between 2018 and 2022.





However, the total number of *Pisonia* seedlings has dramatically changed during the past five years of monitoring with a strong decrease three years after rat eradication (below its original level), and a recent increase in 2022 (**Fig. 13**). This unexpected successional pattern might be explained by both abiotic and biotic factors (*e.g.* fruit, seed and seedling predation by rats and crabs). Natural disturbances such as tree falls and canopy openings caused by strong winds (*i.e.* more light in the understorey) may favoured the seedling recruitment of this light-demanding pioneer species whereas periodic flooding by sea-water or rainfall may destroy its seedlings, contrarily to *Pandanus*, a native tree species forming dense stands (especially in almost pristine uninhabited atolls, such as Morane in the Tuamotu-Gambier, MEYER & PONCET 2022) which seem to be more adapted (and resilient) to changing environmental conditions.

Results in Palmyra have demonstrated a strong increase of *Cocos nucifera* seedlings and biomass five years after rat eradication (WOLF *et al.* 2018, MILLER-TER KUILE *et al.* 2021). The same trend is observed on Motu Reiono where there are also numerous fallen young coconuts in the transects which are no more eaten by rats. The removal of coconut trees, considered as an invasive species with detrimental impacts on atoll native forest ecosystem (YOUNG *et al.* 2010) should be considered as currently done in Palmyra (WEISS 2020), and in the other motus of Teti'aroa where rat eradication was conducted in May-June 2022.

In July 2021, we have set up 10 new transects on Motu Auroa (a small motu located on the north side of the atoll), and added to our seedling recruitment protocol a visual assessment of herbaceous plant cover (using six classes: 0-1%, >1-5%, >5-25%, >25-50%, >50-75%, and >75%) in order to monitor the potential changes in abundance of the creeping herb *Boerhavia tetrandra*, the succulent herb *Portulaca oleracea*, and the terrestrial fern *Microsorum grossum*, which are present on the motu and might be also eaten by rats (and crabs). A first survey was conducted in July 2022, one month after rat eradication (unpub. data).

We strongly recommend a more long-term monitoring of all these permanent transects and quadrats (at least three more years in Motu Auroa), to have a more comprehensive view of atoll forest dynamics and successional trajectories after rat eradication and according to natural disturbances. The strong swell and/or high tide that occured in 2020 and 2021 (MEYER 2021) and in mid-July 2022 may mimic the future impacts of sea-level rise caused by climate change (AMOROS *et al.* 2022).

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<u>APPENDIX:</u> Photos of the 10 study sites (permanent transects) showing seedlings recruitment, plant growth and the effects of natural disturbances (credit: J.-Y. MEYER© except for 2020 by P. DEFILLION©)

<u>Photo 1.</u> *Pisonia* dense forest (TR1): comparison between July 2018 (up left), August 2020 with a *Pisonia* fallen branch (up right), June 2021 (bottom left), and July 2022 (bottom right) with an increase of *Pisonia* seedlings.




<u>Photo 2.</u> *Pisonia* dense forest with *Cocos* (TR2): comparison between July 2018 (up left), August 2020 (up right) with a fallen *Pisonia* branch, June 2021 (bottom left) and July 2022 (bottom right).

Photo 3. *Pisonia* dense forest (TR3): comparison between July 2019 (left), August 2020 (right), June 2021 (bottom right) and July 2022 (bottom left) with young *Cocos* seedlings.

<u>Photo 4.</u> *Cocos-Pisonia* mixed forest (TR4): comparison between July 2018 (left), August 2020 (right), June 2021 (bottom left) and July 2022 (bottom right) with an increase of coconuts on the ground.

<u>Photo 5.</u> *Pandanus-Pisonia-Heliotropium* mixed forest (TR5): comparison between July 2019 (left), August 2020 (right), June 2021 (bottom left) after the passage of a high tide or strong swell, and July 2022 (bottom right) after another strong swell.

<u>Photo 6.</u> *Pisonia* dense forest with *Cocos* (TR6) : comparaison between August 2019 (left), August 2020 (right), June 2021 (bottom left) with a fallen coconut tree, and July 2022 (bottom right).

<u>Photo 7.</u> *Pisonia* dense forest with *Cocos* (TR7) : comparaison between July 2019 after a *Pisonia* tree fall (left), August 2020 (right), June 2021 (bottom left) and July 2022 (bottom right).

Photo 8. Mixed *Pisonia* forest with *Pandanus, Cocos, Guettarda* uncommon (TR8): comparaison between July 2018 (left), August 2020 (right), June 2021 (bottom left) and July 2022 (bottom right) with an accumulation of coral gravels caused by the strong swell.

Photo 9. *Pisonia-Cocos-Guettarda* mixed forest (TR9): comparaison between July 2018 (left), August 2019 (right), August 2020 (bottom left) and July 2022 (bottom right) with an increase of coconut seedlings.

<u>Photo 10.</u> *Pisonia-Cocos* dense forest (TR10): comparaison between July 2019 (left) with land crabs burrows, August 2020 (right), June 2021 (bottom left) and July 2022 (bottom right).