Residual plastic in banana plantation soils: a case study of Costa Rica

Msc Thesis Diede in't Veld

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0. Abstract

From the 1960s on banana plantations started using polyethylene plastic bags to cover banana bunches. Initially, most of the plastic bags were gathered and burned in giant piles after use, however also a large portion was simply left on the field. The plastic that stayed behind remained in the soil and had the potential to accumulate over time, since degradation rates are very low. It is mentioned that the accumulation of plastic in the soil was so severe in some cases that the growth of secondary shoots of the banana plants was inhibited. Around the year 1990 there came a shift in public opinion about the well-being of the environment and Costa Rica became a pioneer in environmentally friendly farming. Since then recycling options have become more refined and all bags are collected and recycled. Assessing the amount of plastic in the soils of these banana plantations gives an unique opportunity to study both the effects of these recycling measures and the residence time of plastic in the soil. In this study we assessed the presence- and the biodegradation of plastics in the soils of abandoned, old (established before 1990) and new plantations (established after 1990) to gain insight in the total magnitude of the problem and to determine the effectiveness of the recycling measures that have been implemented over time. Average values of 7.54±6.76 kg/hectare and 106.63±139.55 kg/hectare were found for surface-, and buried macroplastic. An average value of 7720.1±2809.0 particles per kg was found for microplastic. The microplastic values are in the same order of magnitude as values found in literature. However since methodologies differ the true values might not be the same. From the gathered data we could not conclude whether the recycling measures had any effect over time, due to an insufficient amount of samples and not enough variation in the sampled plantation-ages. We suggest more research to be done on the amount, and the residence time of microplastics in the soil to gain more insight in the effects of, and processes involved in plastic breakdown.

1. Introduction

1.1 Plastic use in agriculture

Due to their versatility and ease of manufacture, plastics have become an indisposable part of our daily lives. Since the introduction of plastic 80 years ago, agricultural plastic use has grown exponentially. In 2019 alone, 12.5 million tonnes of plastic have been used by the agricultural sector worldwide for on-field application. This amount is only expected to increase (PlasticsEurope e.V. 2019). This is not without reason. The use of agricultural plastic has many benefits, it leads to higher yields, reduction of losses, the conservation of water and a decrease in chemical inputs.

Although there are many benefits, agricultural plastic also poses a risk for environmental contamination (FAO et al. 2021). Agricultural plastics are often single-use and directly applied to the field which makes it very easy for the plastic to end up in the soil environment due to mismanagement. These plastics can accumulate over time due to their extremely low breakdown rate. Research on plastic in the environment is still scarce and most of it focusses on aquatic or marine environments. However, It is estimated that soils contain about four times more plastic than the ocean (Qi et al. 2020a). Bläsing & Amelung (2018) predict that with these inputs in certain agricultural areas, plastic content might reach the permille-percent range, similar to soil carbon contents, with effects that are still largely unknown.

1.2 Why research plastic in the soil?

One of the major concerns towards plastic pollution is the fact that larger macroplastic (pieces larger than 1mm) pieces initially break down into micro- or nanoplastics before disappearing completely. These smaller plastics are more mobile within the environment and also more toxic, because of their ability to act as carriers for environmental pollutants such as plasticisers, heavy metals and agrochemicals (Steinmetz et al. 2016). A lot is still unknown about the effects of (micro)plastic in the soil. Reports from various studies are sometimes contradictory and often incomplete (Qi et al. 2020a). Some reports find a lowering of the bulk density and alteration of pore structure, changing the preferential flow of water (Jiang et al. 2017; Wang et al. 2020). Microplastics can also clog soil pores and act as obstacles for air and water, decreasing evaporation and possibly leading to anoxia (Wang et al. 2020). Qi et al (2020b) found that the presence of LDPE debris decreased water holding capacity, while biodegradable plastic debris increased it. Microplastics also seem to be able to affect the ability of clay soils to shrink and swell, which could promote leaching of contaminants into deeper parts of the soil (Wan et al. 2019). Microplastic can also increase SOC contents, which could very well be linked to the change of water retention in the soil (Atuanya et al. 2012).

Furthermore, various selective effects on microbial and biological activity are reported, influencing nutrient cycles (Fei et al. 2020; Li et al. 2022; Ren et al. 2020). These effects seem to be dependent on plastic type, dosage and soil type. Although some studies show some positive effects on this, the general consensus is that there is a negative influence on soil life abundance and diversity (Sajjad et al. 2022, Li et al. 2022). Large soil organisms are also influenced by the presence of microplastics, mostly due to the accumulation of plastic material in their guts and stomachs. Cao et al. (2017) reported that microplastic levels of higher than 1% significantly inhibited growth and increased mortality of earthworms, although 0.5% did not have many effects. High density polyethylene has also been reported to alter soil pH (Boots et al. 2019), which in turns influences many other processes in the soil.

A likely explanation for the different outcomes on these researches on plastic effects is that it is very dependent on the type of plastic, its shape and the soil type in which it is found. In order to gain a better understanding of this, more fundamental research is needed such as measurements of the abundance in various soil types and land uses.

1.3 Plastic degradation over time

Plastic degradation is dependent on many aspects. The type of plastic and its size/shape has great influence on its breakdown rate. There are three main processes that play a role in plastic degradation: Photodegradation, biodegradation and mechanical abrasion (Qi et al. 2020). Figure 1 gives an overview of these processes. Photodegradation is the chemical degradation by UV light, deteriorating the chemical and physical structure of the plastic polymer (Lee & li, 2021). Mechanical abrasion by for instance larger animals, wind and rain physically alters the plastic, tearing and fragmenting the larger plastics into smaller pieces. Biodegradation is the digestion of the plastic by microbes, turning them into inorganic compounds. Biodegradation rate is greatly increased if photodegradation and mechanical abrasion take place first, since this weakens the chemical structure and increases the available surface area of the plastic. The rate of biodegradation is dependent on the types of microbes, their abundance and their abiotic living conditions such as water availability, soil pH and the temperature (Kale et al. 2015). This means that the same plastics could have very different breakdown rates in different soils. High temperatures and water availability lead to faster breakdown rates, theoretically making the tropics an ideal setting for plastic degradation in the soil.

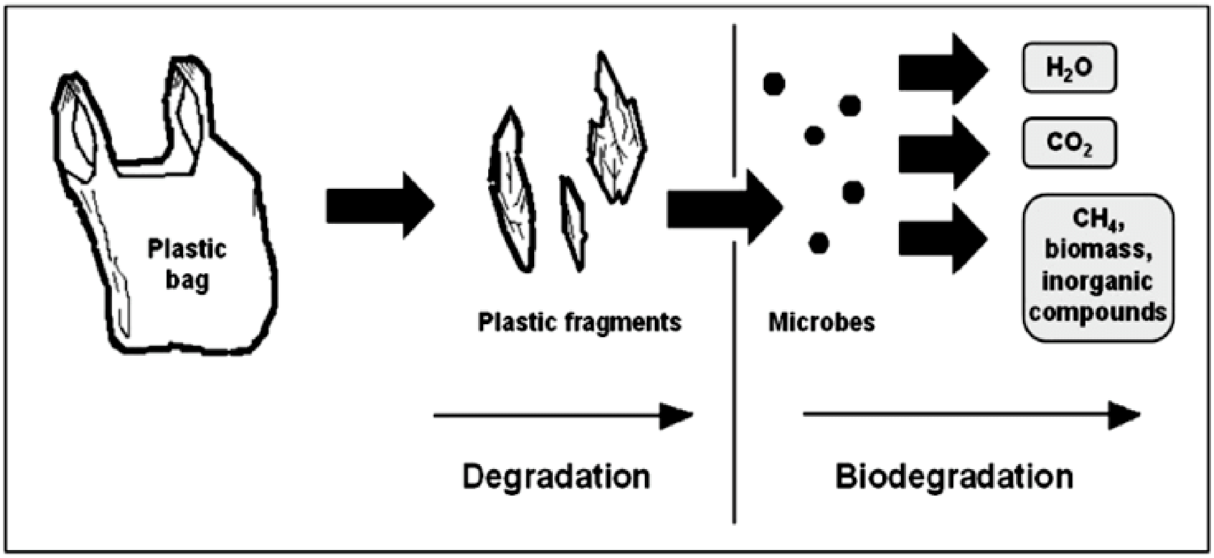

Figure 1: Overview of breakdown process of plastic. Adapted from Islam et al. 2015

Because of the variability of these processes, determining the degradation rate of the plastic within soils is very difficult. Low density polyethylene(LDPE) and polypropylene (PP) plastics are common forms of agricultural plastics and are expected to be most prominent in our study. According to Chamas et al (2020), the estimated breakdown rate is 0.3 – 2.5 micrometre per year for LDPE and 0.3 micrometre per year for polypropylene within soil in Greece under a mediterranean climate. Assuming a thickness of 50 micrometre, it would take 10 to 83 years to degrade a singular plastic bag. However, as mentioned before these are very rough estimations that depend on many aspects. Other research showed a 0% weight loss of regular polyethylene after 4 months under tropical conditions in Thailand (Ratanakamnuan & Aht-Ong 2006).

1.4 Costa Rican banana plantations as Case study

The first commercial banana plantation in Costa Rica was founded in 1870 and by 1890 Costa Rica was a major exporter of bananas to the USA. Since then Costa Rica has grown out to be the second biggest exporter of bananas globally (Workman, 2022). To this day banana production and export is one of the most important industries in Costa Rica. Figure 2 shows the growth of banana export numbers over time.

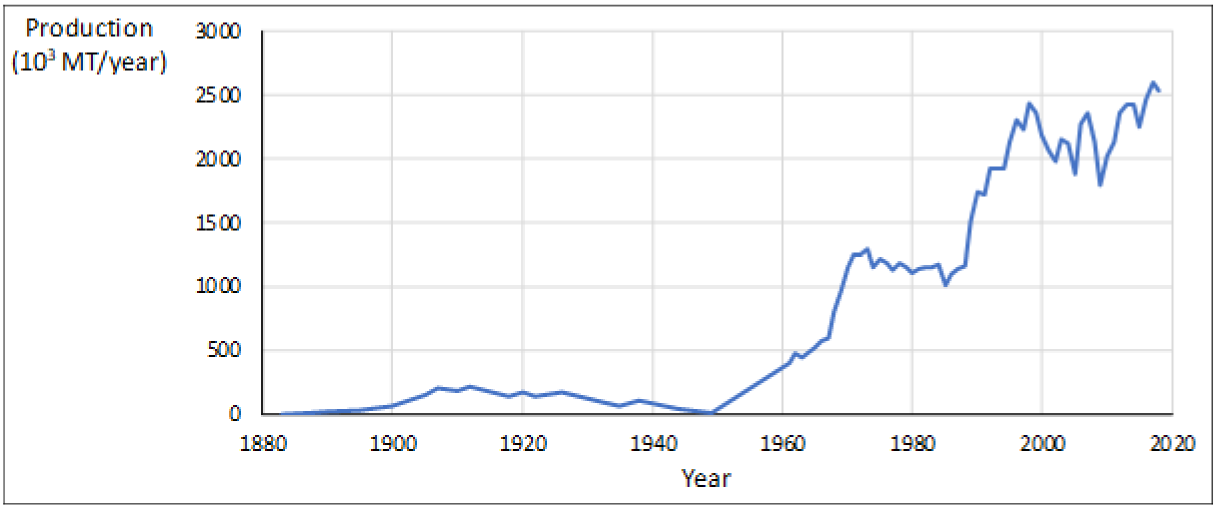

Figure 2: Costa Rican banana exports over time. Adapted from Stoorvogel et al. 2023

From the 1960s on, banana plantations started using polyethylene plastic bags to cover banana bunches in order to improve yield, create a faster and more uniform ripening process and to protect the bananas from an excess of sunlight. Additionally the bags were laced with pesticides, improving the protection against bugs and other pests (Santosh et al. 2017). This practise of bagging the banana bunches has become normalised in nearly every banana plantation around the world. Next to the plastic bags, polypropylene twine was used to stabilise the trees and prevent falling during storms, and under the weight of the banana bunches themselves.

Around the year 1990 there came a shift in public opinion about the well-being of the environment. This was the main reason why people were looking into the collection and the recycling of these plastics. Costa Rica as a country has become a pioneer in the implementation of sustainable, environmentally friendly policies over the years. More than 98% of its energy is renewable, and forest covers 53% of the country's land area (UNEP, 2019). This can also be seen in their approach on the plastic waste management of its banana plantations. One of the innovations they implemented was to cut the bags according to the size of the actual individual bunch on site instead of using uniform sized bags for every bunch. This was introduced in 1992 in Costa Rica, saving 25% in plastic material (E.A.R.T.H., 1992).

One of the things that makes recycling of these plastic bags difficult is the fact that they are laced with pesticides, making them unsuitable for recycling into products for human consumption (Cadena et al. 2021). A precise cleaning process is needed before recycling can take place. This might make small-scale recycling difficult since it becomes economically less attractive. Therefore, the distance to a recycling plant might have great influence on the degree of recycling that takes place on site (Davis et al. 2020). However, nowadays recycling options have become more refined and currently, in Costa Rican plantations, all bags are collected and recycled at the factory of the company Recyplast (Lieben, 2023). At the end of its lifecycle the bags are mostly recycled into pallet corner pieces for banana transport (Lieben, 2023). Other possible recycling options include fence posts (Kopetski 2002) and in 2014 it was found that non degradable plastic waste from banana plantations could also be added to bitumen or asphalt to improve its properties (Villegas-Villegas & Loría-Salazar 2014).

Currently there are also more environmental-friendly options available for the production of banana bags. Polylactic acid (PLA) plastic is a bioplastic, meaning that it is derived from plant based materials, and is labelled as biodegradable. Ho et al (1999) investigated the degradation of PLA films on site of banana plantations in Costa Rica. In their study it is estimated that the PLA films needed three weeks to visually degrade when incorporated in compost heaps, and 6 months when incorporated in the soil. This does not mean that PLA always degrades easily. Karamanlioglu & Robson (2013) found no weight loss of PLA after one year of burial at 37 degrees.

There are also land rejuvenation projects going on. This means that the production of banana is brought to a halt, in order to reshape the land. According to Chiquita (2019) their land rejuvenation project has removed up to 1 tonne per hectare of plastic from the soil, leading to a 25% increase in yield. Although the increase in yield can also be attributed to the reshaping of the land, it does show that there is a big emphasis on the degree of residual plastic in the soil.

1.5 How much plastic could we expect?

Quantifying how much plastic was actually used during the period 1960-1990 is difficult in hindsight. But, Russo and Hernández (1995) made an estimation of the amount of plastic that was used during this time in Costa Rica. They estimated that 67 kilogrammes per hectare of polyethylene plastic bags were used and 80 kilogrammes of polypropylene twine was used per hectare. These numbers exclude the amount of plastic that was used for the packaging process. After usage, most of the plastic bags were gathered and burned in giant piles, however it was reported that a large portion was left on the field together with almost all of the twine material (Kopetski et al. 2002).

Plastics that were left on the field often did not stay there. They were carried away by either water or wind and polluted rivers and other parts of the environment (Kopetski et al. 2002). Since the bags are non-biodegradable and impregnated with contaminants like pesticides, they form a major threat to the environment (FAO 2021). Plastics that are not caried away have the potential to accumulate in the soil over time, since degradation rates are so low. It is mentioned that in some cases the accumulation of plastic in the soil was so severe that the growth of secondary shoots of the banana plants was inhibited (Russo and Hernández 1995).

A very rough calculation of the possible amount of plastic that could be found would give 147 kg/ha of plastic (67kg of bags + 80kg of twine) * 60 years (1960-2020 roughly) = 8820 kg per hectare as a maximum, equalling 8.8 tonnes, making the statement of Chiquita possible. However, in this calculation all plastic that is used ends up in the soil, does not degrade and the input does not decrease over the years, making it completely unrealistic. Still, it does give an estimation of the absolute maximum values we could expect.

Nowadays banana farming in Costa Rica is very modernised. Over the years, metal cable constructions have been set in place to help with the transportation of banana bunches after harvest. This means that the banana bunches have to travel less, reducing the chances of losing the plastic bags during transport. The usage of plastic bags has also gone down over the years. The FAO (2021) estimates that currently 45 kg/ha of plastic bag material is used in banana plantations. This is an estimation of the world-wide average and although this might differ from reality in Costa Rica it seems there is a reduction in usage. In one of the plantations, it was mentioned that 80kg of bags were used, together with 29kg of twine material. The differences in weight of the bags could be explained by a possible difference in thickness of the bags. Protection bag usage is often measured in meters by the plantation, but not in weight. Bag thickness differs in some plantations, and is often changed throughout the year to accommodate for the seasonal differences in sunlight received by the bunches (Lima et al. 2020).

1.6 Research outline

Plastic pollution of the soil is a problem of a still unknown scale. There is little insight on its abundance, breakdown rates and effects on the soil. In general, (micro)plastic dynamics are not yet well understood, and more fundamental research is required under as many different land uses and conditions as possible. Since the 1960s bananas have been cultivated using plastic bags around each bunch. During these years there was little to no regards to the environmental pollution of these plastics. This makes it likely that old banana plantations contain much plastic residue in the soil. Overtime the Costa Rican banana industry became more aware of this problem and implemented improved sustainability measures around the year 1990. Comparing the old and new plantations in terms of plastic pollution will give an insight of the effectiveness of the sustainability measures that have been applied over the years, and possibly identify any gaps that could be filled to make the banana production even more sustainable. Additionally, this presents an unique opportunity for environmental plastic research. The historical use of plastic is known within each plantation, therefore the concept of 'Space for time' can be applied. Sampling different plantations of different ages creates an overview of differences in time, while still measured at the same time. This creates insight in the effects of the time-dimension without actually having to wait multiple years.

1.7 Research Questions:

Can the effect of the improved sustainability measures of the 1990's be found back in the plastic pollution of banana plantation soils?

1. What degree of plastic residue can be found in both abandoned and currently used banana plantation soils in Costa Rica?
2. What factors influence the abundance of plastic residue in the soils of banana plantations?
3. What is the order of magnitude of the plastic degradation rate in Costa Rican banana plantations?

2. Methods

2.1 Site Description

The Caribbean side of Costa Rica is where most of the Costa Rican banana production is concentrated, Both historically as well as today (Bellamy 2012). Within the Caribbean part of Costa Rica exists a divide between two major soil groups: Soils formed by alluvial deposition with volcanic origin in the western parts, and calcareous mineral soils in the east. The division between these soil types is roughly located along the Reventazon river. (Nieuwenhuyse 1996)

Banana plantations themselves are structured around metal transportation cableways. These transportation cableways separate the plantations into sections, or production zones. Input material such as fertilizers are brought through the cableways towards the banana plants, and harvested banana bunches, including associated plastics, are carried to the nearest transport cable after which they are transported to the packing facility.

Due to the weather conditions, Plantations frequently get flooded by rainwater (Kopetski 2002). Therefore it is very important for banana plantations to have a good drainage network. In practice this means that every 15 metres a ditch is made, often perpendicular to the transportation cableways. This drainage system form a potential way for the agricultural plastics to leave the plantation and enter the aquatic environment.

2.2 Plantation Selection

Plantation selection was done based on soil type and the age of the plantations, since the soil type can have a big influence on the plastic degradation rate (Qi et al. 2020).

Around the year 1990 enhanced sustainability measures for plastic banana bags was set up (Russo and Hernández 1995), therefore we are interested in the plantations that were established before or after 1990. Furthermore abandoned plantations are interesting since after being abandoned the input of plastic stopped. The age of the plantation was asked to the farmers or determined using satellite data.

This led to 6 groups considered: Old (established before 1990), new (established after 1990) and abandoned plantations in both soil regions. Though initial selection was based on these groups, In the end the plantations that were visited were based on availability: Many farmers were asked, few replied and gave permission. This also means that all visited plantations were all national plantations, so not the ones owned by large multinational companies such as Chiquita or Dole since they did not give permission.

2.3 Sampling strategy

Within each plantation, two to five locations were sampled. After selecting a location, a distance of 15 meters from main cableway was taken to eliminate the distance from the cable as a possible factor for variation of the amount of plastic in the soil. Since all banana bunches (including the plastic bags) are transported towards the nearest transportation cable you could expect there to be more plastic close to the cableways than further away.

For each location a photo was taken and GPS locations were stored. The exact location age and, in case replantation had taken place, the replantation age were determined by asking the owner of the plantation. In case this was not possible the (replantation)age was determined using freely available satellite data. The soil coverage was also classified into three categories: No coverage, half covered and fully covered. Figure 3 shows examples of each of these categories.

Figure 3: Examples of Grass cover classes within the banana plantations , No cover (left), Half cover (middle), Full cover (right)

2.3.1 Surface macroplastic sampling

On each location a transect was walked parallel to the cableways. All visible surface macroplastic within one meter distance of the transect was collected. An example of this would be to walk 15 meters and therefore have 30m^2 coverage. In case there were any dead banana leaves covering the soil these were moved to looked underneath.

2.3.2 Buried macroplastic sampling

In order to determine the amount of buried macroplastic, two to six holes of 15x15x10 centimetre were dug with a shovel and filtered on the spot by hand, based on the amount of available time. All visible plastic was collected in one bag in order to create a composite sample, along with a note of how many of the dug holes contained any visible plastic. In case plastics were only partially within the space of 15x15x10 centimetre, scissors were used to cut of the part that was inside the sampling area. Samples were taken in a transect parallel to the surface macroplastic transect. This is done because of the fact that some of the surface macroplastic is also partially buried, disturbing the sampling location after removal. Any macroplastic that was on top of the soil was not included in the sampling.

2.3.3 Microplastic sampling

Additionally between two and four soil samples were taken with a gouge for the determination of microplastics in the soil. The locations for sampling were along the walked transect. Only the top 15 centimetre was sampled.

All samples were kept in paper bags to prevent plastic contamination during storage.

2.4 Laboratory work

2.4.1 Surface and Buried macroplastic

In the laboratory, the marcoplastic, both buried and surface, was cleaned under the sink and left to dry. After 24 hours of drying the following weights were measured: Blue bags, Twine, Labels, and Other. During result analysis two classes were used: blue (banana bag) macroplastics and the total macroplastics.

2.4.2 Microplastic

For microplastic analysis the soil samples were dried in an oven at 40 degrees for 24hours. After that the samples were grinded to make them uniform. In case larger macro plastic fragments were present within the soil sample, these were weighed and added as a note to the microplastic measurements. For each sample approximately 5 grams were weighed and added to a plastic test tube. Afterwards a saturated NaCl solution is added to roughly 20-25millilitre. The solution was made before analysis using regular table salt, up to a density of 1.156 Kilogram/litre. The salt solution was chosen instead of water because of the possibility of certain plastics having a higher density than 1. In order to determine whether the salt solution was dense enough for the plastic to float, some pieces of the macroplastic were used to check.

Samples are shaken by hand for roughly ten seconds to mix soil and water after which the samples were put in a shaking machine for twenty minutes to ensure soil aggregates were broken and the sample was well mixed. Next the sample is put in the centrifuge for 30 minutes at 2000 rotations per minute. Before putting the samples in the centrifuge, a pipet is used to clean the inner sides of the test tube, ensuring all soil (and plastic) particles are separated by the centrifugal process. The cleaning is done using the NaCl-solution, in order to not change the density of the substrate. After centrifuging, the supernatant and solution is poured through a labelled paper filter, leaving only the heavier soil particles as precipitate in the test tube. This procedure is repeated two more times more to ensure all soil aggregates are broken and all microplastic ends up on the filter paper.

The filter paper used was 'Whatman qualitative filter paper grade 1', with a filter size of 11 micrometres. Therefore all particles with a lighter density than 1.156 kilogram per litre and a size larger than 11 micrometre were left on the filter paper, and therefore included in further analysis. The filter papers were stored between two sheets of paper towel, to prevent any airborne microplastics from entering the filters. Figure 4 shows an example of microplastic samples on the filter papers.

Figure 4: Microplastic samples on filter paper

The filterpapers were studied under a microscope. The following microplastic categories were counted: Blue bag microplastic, Red microplastics, less certain-red microplastics, transparent microplastic and other (mostly differently coloured microplastics and different distinctive shapes). The distinction between certain and less certain red microplastics comes from the fact that it the difference between certain root types and the red microplastic seemed to be very small. In the end both grouped together and were counted towards the total microplastic amount. For analysis purposes the plastics were grouped into either blue bag microplastic or total microplastic.

The paper filter samples were subsampled to reduce the time needed of analysis. This means that only half of the filter paper was used to look for microplastics, and the end results were multiplied by two. In order to asses the accuracy of this method four samples were sampled completely.

2.5 Burial test

Additionally two burial test were set up. Used banana bags were taken from a plantation and samples of roughly 15x15centimetre were cut out, washed and weighed. It is important that a bag that has already been used is taken instead of a completely fresh one, since the used bags are the ones that generally end up in the soil, and some degree of photodegradation has already taken place.

Appendix 1 gives an overview of the burial tests that have been initiated. After the burial period has passed, the bags are dug up, washed and weighed again in order to determine the weight loss. Both burial tests were initiated in the alluvial soils with volcanic origin.

The first burial test contained one bag that was left in the soil for 71 days. The second burial test has not yet been harvested, but is set up for later data collection. In this test, twelve plastic banana bag samples were buried at a depth of seven centimetre. After each year three of the samples will be dug up, washed and weighed again, to accurately assess the amount of weight loss, from which a breakdown rate can be calculated.

2.6 Data analysis

After filtering of unsuitable locations and measurements, 30 sampled locations remained. The averages and standard deviations that are calculated in this report are those of the sampled locations, not those of the plantations themselves. This is due to the fact that the plantations are not heterogeneous in aspects of age, soil coverage and whether replantation has taken place. In order to determine relationships between predictor and prediction variables correlations, T-tests and ANOVA analyses were calculated in Excel.

3. Results

In total nine banana plantations were sampled, from which a total of 30 locations were sampled. Table 1 shows an overview. Plantations have been made anonymous to prevent any negative publicity.

Table 1: Overview of sampled plantations and locations

Plant. Name	#	Location age	Years since replantation /abandonment	Plant. Name	#	Location age	Replant age
M1	2	55 years	10 years replanted	V1	3	35 years	10 years replanted
					1	35 years	1 year replanted
					1	35 years	-
M2	1	30 years	-	V2	3	35 years	-
	1	20 years	10 years abandoned		1	35 years	1 year replanted
M3	3	30 years	1 year replanted	V3	3	32 years	-
	3	25 years	-		1	32 years	1 year replanted
M4	2	30 years	-	V4	3	20 years	-
				V5	2	45 years	15 years abandoned

3.1 Observations

3.1.1 Surface macroplastic

Found surface macroplastic mostly consisted of polypropylene twine, followed by both label- and plastic bag material in roughly equal amounts. Only in four out of the 30 sampled locations any other type of macroplastic was found. During collection banana leaves that were covering the soil were moved to look underneath, however the vast majority of found macroplastic was found on soil without cover.

Plastic bag material that was found was generally small in size. Either it was a small part of a bag that had been torn off, or it consisted of the very small round disks that were left after perforating the bags incompletely (Figure 5). Large pieces of blue macroplastic were rarely seen, and no complete bags were found. Found blue bag plastic seemed to be intact most of the time, making collection very easy. In a few instances this was not the case and the macroplastic was too fragile to be collected (Figure 5). In these cases the plastic was fragmented and soft in touch, and almost impossible to separate from the dirt. These highly degraded plastic bags were not only found in older-, but also in the newer plantations.

Figure 5: Blue bag macroplastic found in the field: Small disks left after perforation (left), Highly degraded blue bags found within plantation M4 (middle) and V4 (right)

The twine material was often half-buried, yet visible from the surface. Because of this, collection was a bit tricky, and sometimes macroplastic was collected that was actually sub-surface level, giving a slight overestimation of the level of surface macroplastic. Still it was undoubtably the twine macroplastic that was most present on the plantation soil. Twine was often still bound to old plant-stumps that had been cut.

3.1.2 Buried macroplastic

The subsurface macroplastic that has been found consisted almost exclusively out of plastic twine material. Some small fragments of blue bag macroplastic have been found, but these were mostly the small round particles resulting from perforation of the bags (Figure 5). Only twice a larger piece of blue macroplastic was found.

Degradation of the twine material in both surface and buried macroplastic could be seen by deterioration of colour, and a 'loosening' of the twine (Figure 6). Plantation V3 had used blue twine material before they switched to orange twine 20 years ago. The youngest blue twine that was found did not show much deterioration in colour, but did seem looser than the new orange twine that was used (Figure 7). In no cases the plastic twine material was soft, like the blue bag material found. However in some of the samples of the abandoned plantation of V5, the twine was brittle, and broke down into smaller pieces of roughly a few centimetres once shaken or rubbed. Plantation V5 was the only plantation in which black twine was found. In plantation V1 some orange twine was found that lost some smaller particles when rubbed, although this was by far not as brittle as the material found in plantation V5.

Figure 6: Two strings of twine macroplastic, one very young and the other deteriorated in colour and no longer as tightly woven as the other. Taken from plantation V1 (left),

Figure 7: the youngest blue twine material found (left), together with older blue twine (bottom right) and some younger orange twine (top). Found on plantation V3

3.1.3 Microplastic

Microplastics were categorized in different colour classes. The colour distribution is shown in figure 8. More than half of the found microplastics were transparent.

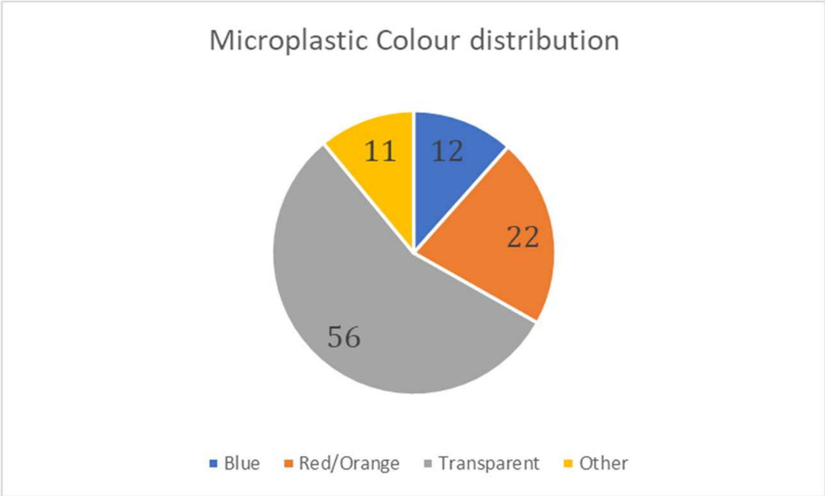

Figure 8: Distribution of observed microplastic colour classes

Blue microplastic was mostly found in the shape of fibres such as shown in figure 9. Few fragments were found as well. Found fragments were often much lighter of colour and often only partially coloured (Figure 9), furthermore their textures differed from the fibres. Therefore these fragments were classified separately.

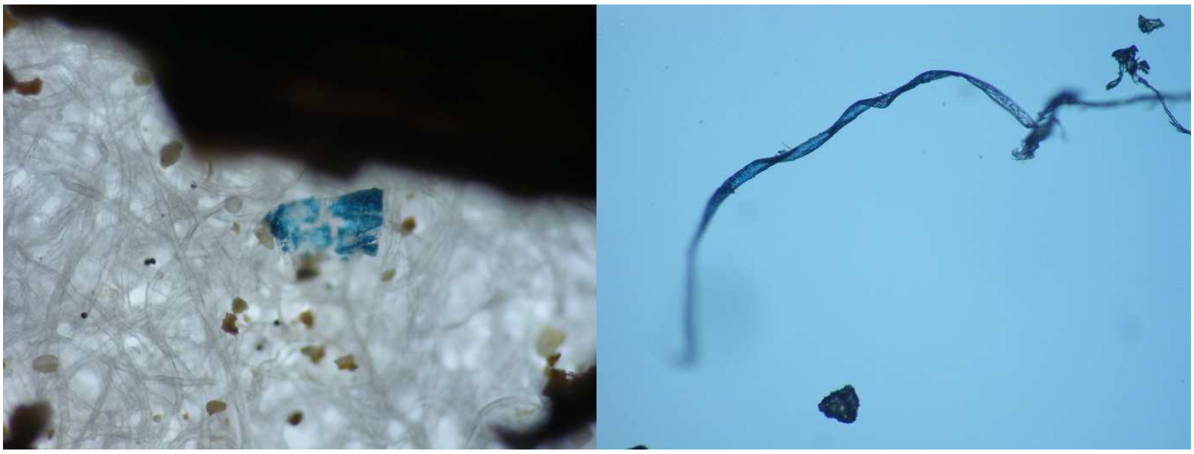

Figure 9: Blue fragment (left) and fibre (right) under microscope.

In order to verify the origin of the microplastic, some of the blue bag macroplastic was put under the microscope as well. Here we can see the formation of microplastic fibres(Figure 10) and microplastic fragments (Figure 11).

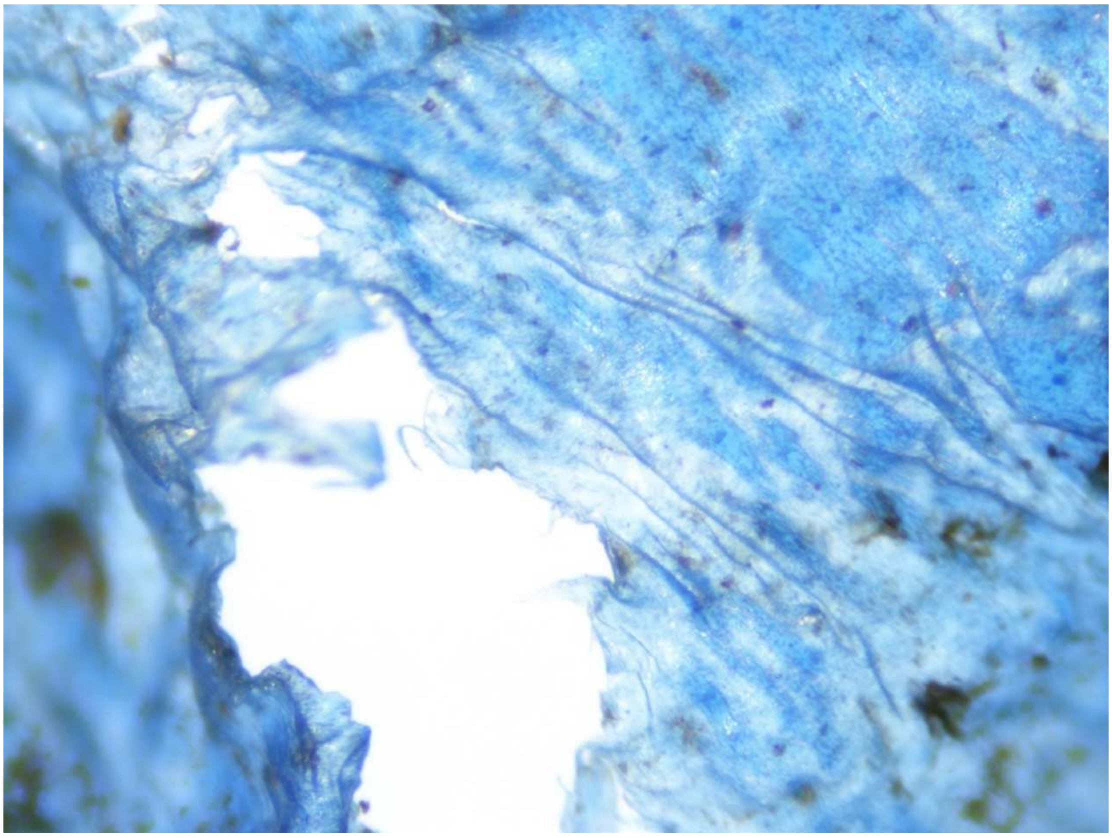

Figure 10: Blue bag macroplastic under the microscope with potential microplastic fibres forming at the edges

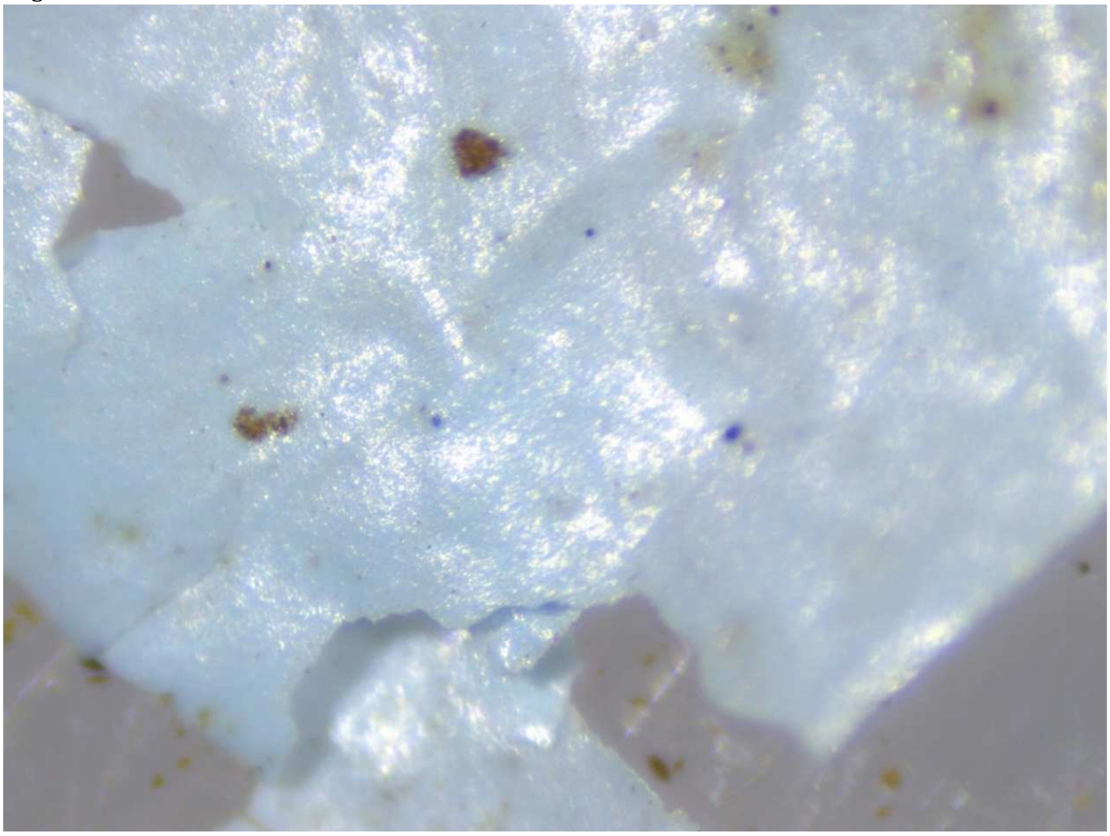

Figure 11: Blue bag macroplastic under the microscope breaking down into potential microplastic fragments.

Degradation of the blue microplastics could be found in loss of colour. Figure 12 shows a blue microplastic fibre that is losing its colour. These decoloured microplastics could be found in the samples of both young and older plantations.

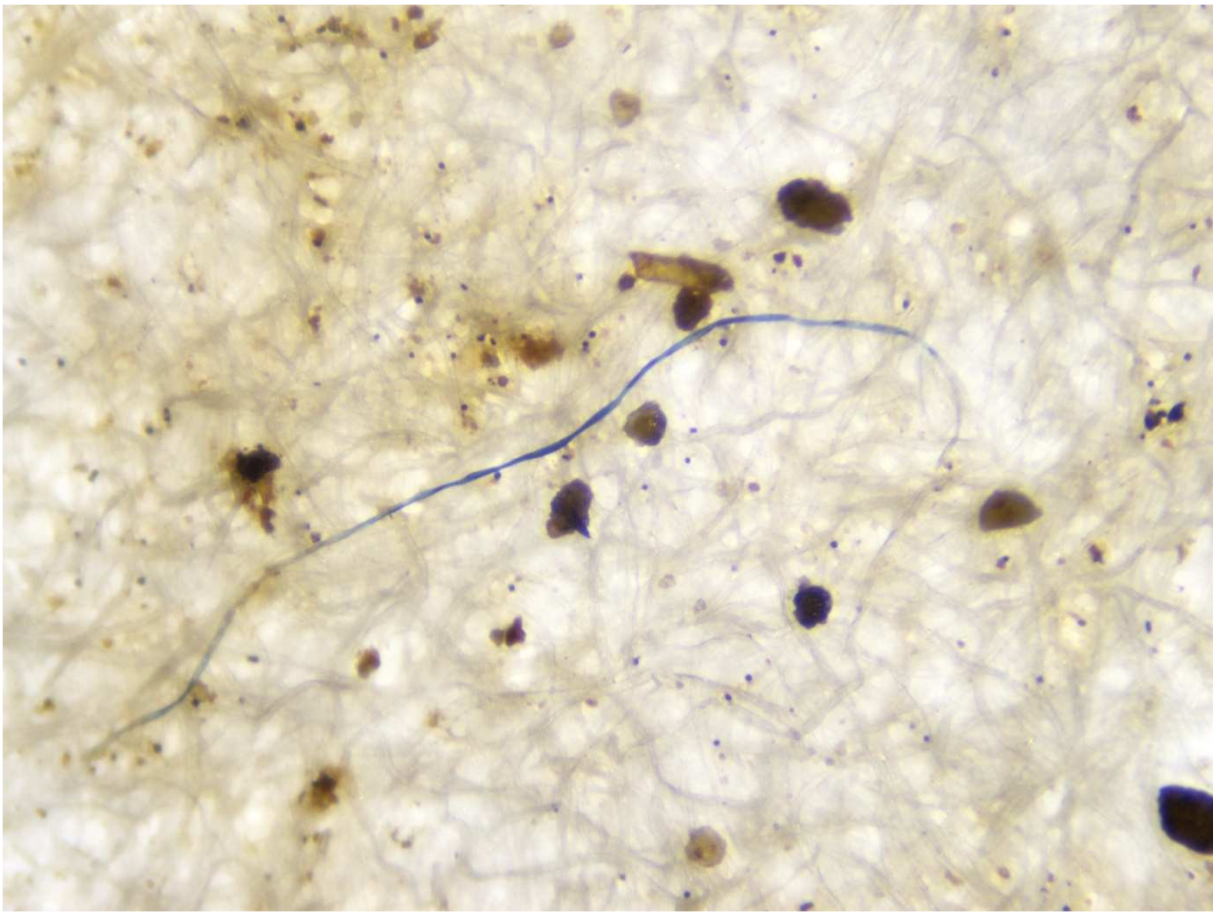

Figure 12: blue microplastic under microscope, showing deterioration of colour. Both ends of the plastic have less colour than the middle part.

Red/orange microplastics were mostly encountered in fibre form as well. However there were differences in the fibres. Examples of these microplastics are shown in figure 13. Some were flat, with a less explicit texture than the blue bag microplastics. These fibres sometimes seemed to have segments of some kind (Figure 13), where the microplastic either narrowed or showed a decolouration at the end of the segments.

The other type of found red/orange microplastic is more rounded, and is segmented more clearly (Figure 13) . Sometimes these microplastics sometimes split in angular corners of nearly 90 degrees, as can be seen in the figure. These microplastics were counted separately.

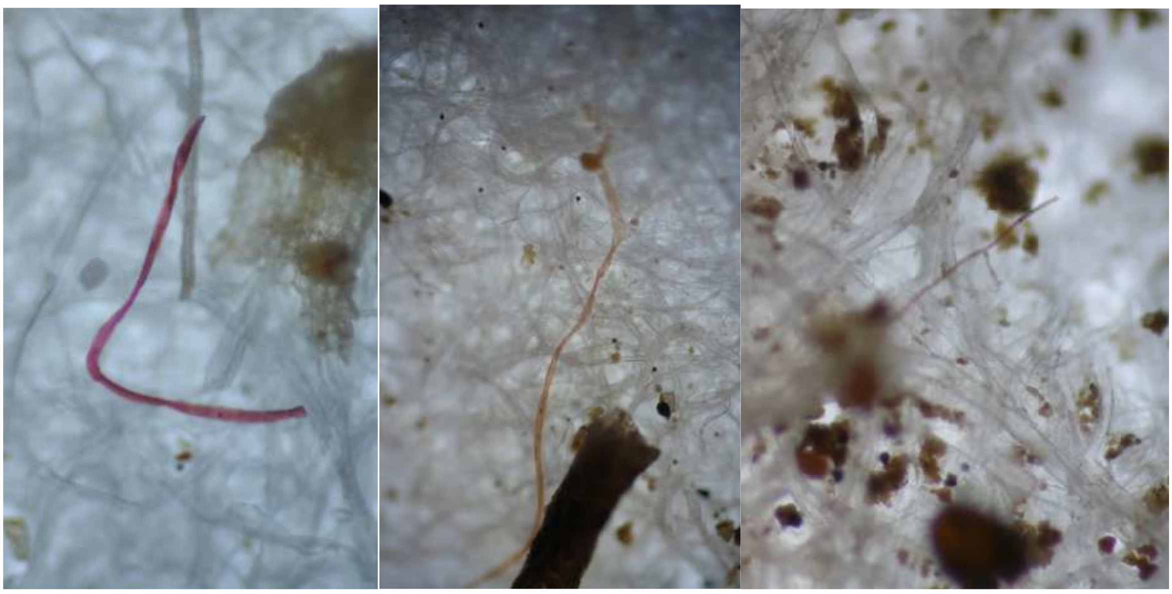

Figure 13: Red microplastics under microscope. Clear red (left), Slightly segmented orange (middle), Red with clear segments and sharp corners (right)

Other microplastics consisted of transparent materials, or those of different colours. These came in various shapes, however fibres remained the dominant form. Two examples of other microplastics are given in figure 14.

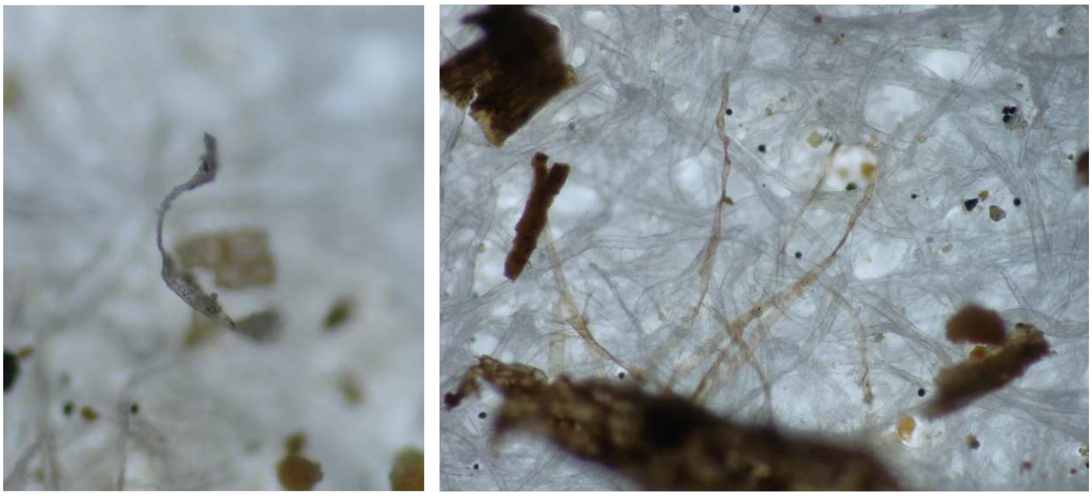

Figure 14: Examples of other found microplastic under microscope: Transparent fibre (left), Brown fibres + pellet (right)

In order to determine the effectiveness of subsampling the filter paper for microplastics, four samples were sampled completely and compared with half sampling. Table 2 shows the results of the subsample versus fully sampled filter papers. The differences between subsample and full sample are biggest for blue microplastic. For sample 3 the subsample showed no blue microplastic, and 1193 particles per kg when fully sampled. Differences for total microplastic are less extreme, with an average difference of +16%, with a highest percentage difference of 32% for sample 1.

Table 2: Results of subsample accuracies

	Blue Microplastic (#/kg)			Total Microplastic (#/kg)		
	Half sampled	Fully sampled	% difference	Half sampled	Fully sampled	% difference
Sample 1	805	1006	25	7646	10060	32
Sample 2	402	604	50	6036	7445	23
Sample 3	0	1193	-	11531	10736	-7
Sample 4	1200	1200	0	2600	4200	17

3.2 Overview of collected data

3.2.1 Macroplastic averages and plantation distribution

The average surface blue macroplastic found was 0.44±0.77 kg per hectare. For buried macroplastic the average value is 1.18±5.69. However this is including the abandoned locations, where no blue macroplastic was found. Only counting plantations that are currently in use, the averages become 0.48±0.79 and 1.33±6.03 kg per hectare respectively. The blue buried macroplastic measurements contain one major outlier, of 29.63kg per hectare. If this measurement is excluded the average for blue buried macroplastic drops to 0.09±0.25 kg per hectare.

In figure 15 the distribution of blue surface and buried macroplastic throughout the different plantations is shown in boxplots. M1 clearly has the highest blue surface macroplastic levels, However the buried macroplastic for this location is missing. Location V5 consisted only of abandoned area. No blue macroplastic was found here. In four out of eight plantations no blue buried macroplastic was found and only in V3 and V4 a piece of blue macroplastic larger than the perforation plastic (roughly 0.002grams per particle) was found. For plantation V4 this leads to one observation of 29.63kg per hectare, bringing it’s average to 9.93kg per hectare. This dwarfs the other measurements and creates a high variance within the dataset.

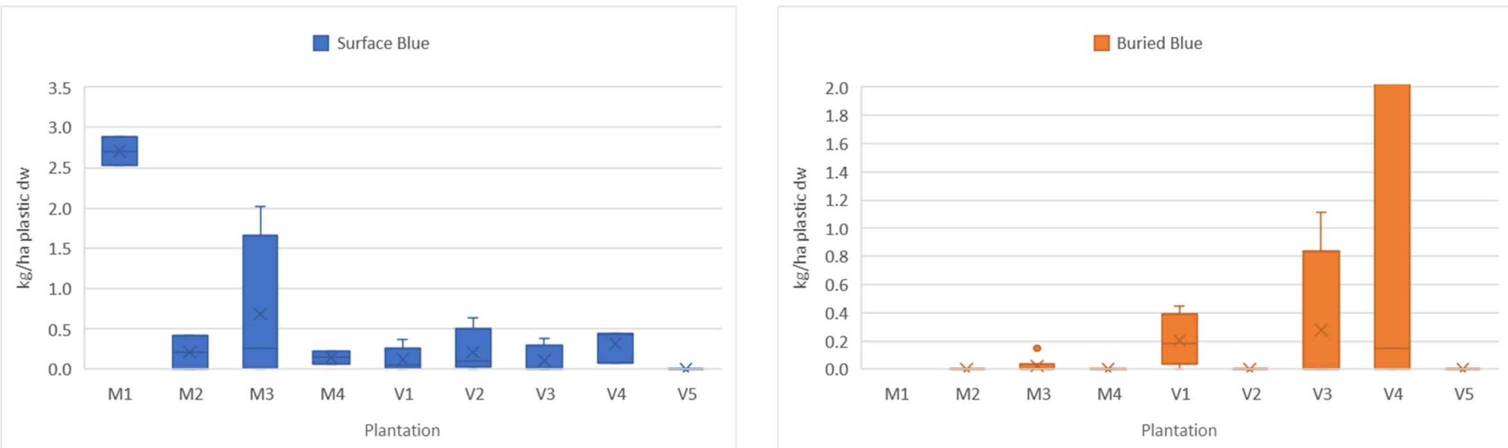

Figure 15: Boxplots of blue surface-, (left) and blue buried macroplastic (right) for each sampled Costa Rican plantation. * Plantation V4 buried top value 29.63, Average 9.93. All weights are given in dry weight (dw)

The average surface total macroplastic found is 7.54±6.76 kg per hectare. For total buried macroplastic the average value is 106.63±139.55. When excluding the abandoned plantations the averages become 7.18±6.09 and 111.71±140.90 kg per hectare. The lower value for surface macroplastic indicates that the sampled abandoned plantations had an above average level of surface macroplastic.

Figure 16 shows the distribution of the total surface and buried macroplastic. Contrarily to the blue macroplastic results, plantation M1 does not have a high surface macroplastic value compared to the rest. M4 has the highest average value of 22.34±0.06, the boxplot is very narrow here since the two observations are so close to each other. For the buried macroplastic V2 has the highest average, together with the widest boxplot. V1 shows very low values as does plantation M2. Buried macroplastic values for plantation M1 and V5 are missing.

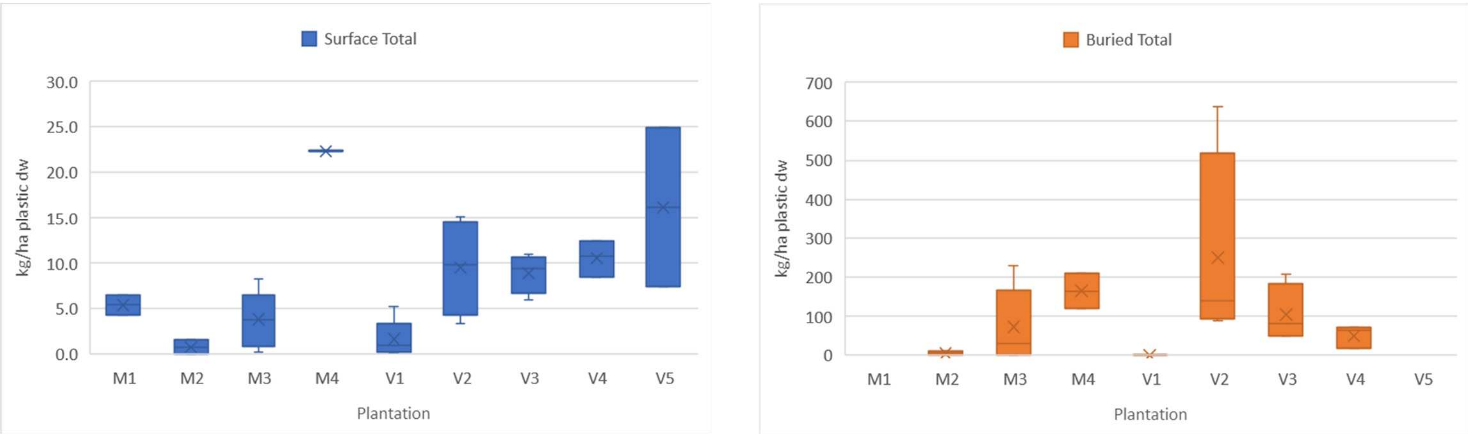

Figure 16: Boxplots of total surface-, (left) and total buried macroplastic (right) for each sampled Costa Rican Banana plantation. All weights are given in dry weight (dw)

The buried macroplastic samples consisted of composite samples. Figure 17 gives an overview of the ratio of subsamples that contained macroplastic against subsamples that did not contain any macroplastic. In total 55% of the subsamples contained any amount of macroplastic. The highest percentage is 100% for plantation V5, the total buried macroplastic measurements for this location were excluded because an overestimation had taken place. The next highest percentage is 83% for plantation V1. This does not correspond with the highest amount of blue-, or total buried macroplastic found.

M1	
M2	0.25
M3	0.33
M4	0.67
V1	0.83
V2	0.56
V3	0.50
V4	0.44
V5	1.00
Grand Total	**0.55**

Figure 17: Ratios of subsamples for buried macroplastic that contained any amount of plastic

3.2.2 Microplastic averages and distribution

The average Blue microplastic values found was 775.9±512.9 particles per kg of soil, while for the total microplastic 7720.1±2809.0 particles per kg is average. In all

Abandoned locations (blue) microplastics were found, therefore there is no direct reason to exclude them from the average values.

The microplastic distributions per plantation are displayed In figure 18. M1 has the highest value for Blue microplastic, which goes together with the highest average value for blue surface macroplastic, as seen before in figure 15. Plantation M2 has the lowest value for total microplastic. V1 has the highest average value for total microplastic. M4 and V5 consist of only one measured location and therefore do not show any spread on the boxplot. The values of the blancs (BL) are 800 for Blue- and 3400 for the total microplastic. In the case of the blue microplastic this is a higher than the average value.

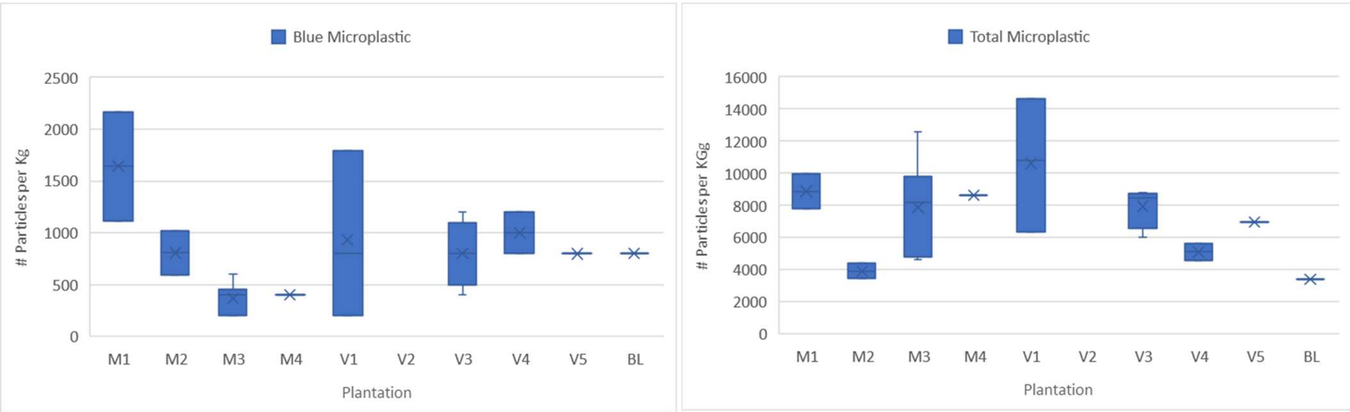

Figure 18: Boxplots of Blue microplastic (left) and total microplastic (right) per plantation. Blanks are shown under the label BL. Unit is in number of particles per kilogram of soil

3.3 Correlations between plastic classes

No strong correlation between the different classes of plastic could be found. The strongest correlation found has a R-squared of 0.093, for the correlation between blue surface macroplastic and blue microplastic. However, both the blue- and total buried macroplastic contain one major outlier in the dataset. After removal of this one outlier correlation factors became stronger. In the case of total surface macroplastic and total buried macroplastic this led to a correlation factor of 0.276, which is still not considered strong, but is much stronger than any of the other results. A visualization of the correlation factors is given in appendix 2.

3.4 Explaining factors

In this section the effects of several possible predictor variables on the different plastic categories are explored through various types of statistical analyses.

3.4.1 Soil type

The influence of the two different soil types have been assessed using T-tests (Table 3). The only significant difference between the two soil types was found for blue bag surface macroplastic, showing that there is more plastic to be found on the surface of non-volcanic soils. The effects of the one big outlier in the blue buried macroplastic can also be seen well in the variance of the blue buried macroplastic in volcanic soils. Due to this the difference is not significant even though the means are very different.

Table 3: T-test results of differences of average values for every plastic type between the two soil types. Significant P-values highlighted in bold.

	Non-volcanic soil		Volcanic soil		
	Average	STD	Average	STD	P-value
Blue Surface (Kg/ha)	0.93	0.18	1.21	0.04	**0.048**
Blue Buried (Kg/ha)	0.02	2.11	0.00	58.03	0.304
Blue Micro (#/Kg)	691.09	887.90	366397.07	218237.49	0.436
Total Surface (Kg/ha)	7.29	7.11	61.73	23.08	0.945
Total Buried (Kg/ha)	86.05	130.95	8598.36	28901.13	0.449
Total Micro (#/Kg)	7703.79	8190.53	7554834.31	9529880.34	0.723

In this analysis, abandoned plantations are included. A separate analysis excluding the abandoned plantations was also performed. The results of this can be found in Appendix 3. Although the P-values slightly changed, this did not influence the results much. Blue surface macroplastic remain significant while the others remained insignificant.

3.4.2 Grass Cover

ANOVA single factor analysis was performed to assess the role of soil coverage on found plastic (Table 4). The only significant difference that was found was on the total surface macroplastic. A P-value of 0.09 can also be found for Blue microplastic, close to significant. However it can also be seen that the mean value of fully covered soil is actually higher than that of the half covered soil.

Table 4: ANOVA results of differences of averages values for found plastic between the three grass cover classes. Significant P-values highlighted in bold.

	No grass cover			Half grass cover			Full grass cover			
	Average	Variance	Count	Average	Variance	Count	Average	Variance	Count	P-value
Blue Surface (Kg/ha)	0.58	0.94	13	0.50	0.56	9	0.13	0.03	8	0.421
Blue Buried (Kg/ha)	0.11	0.09	11	3.31	97.43	9	0.12	0.03	7	0.404
Blue Micro (#/Kg)	1010.32	276788.44	8	475.51	101602.15	8	881.60	348849.94	5	0.094
Total Surface (Kg/ha)	10.53	27.96	13	8.47	70.52	9	1.64	3.29	8	**0.008**
Total Buried (Kg/ha)	95.90	3650.41	9	92.76	7855.53	9	161.98	100636.17	4	0.701
Total Micro (#/Kg)	7756.83	2178352.67	8	7555.49	7751736.29	8	7924.71	21966548.99	5	0.975

3.4.3 Plantation age

The correlations of the different types of found plastic and the plantation ages have been plotted in Figure 19. The highest R-squared value that was found is 0.27 for the correlation Between blue microplastic and plantation age. Closely followed by the correlation factor for blue surface macroplastic of 0.26. These are both still considered to be weak correlations. These correlations do clearly outperform their total macroplastic counterparts. In the case of the total surface macroplastic a negative correlation with age is seen.

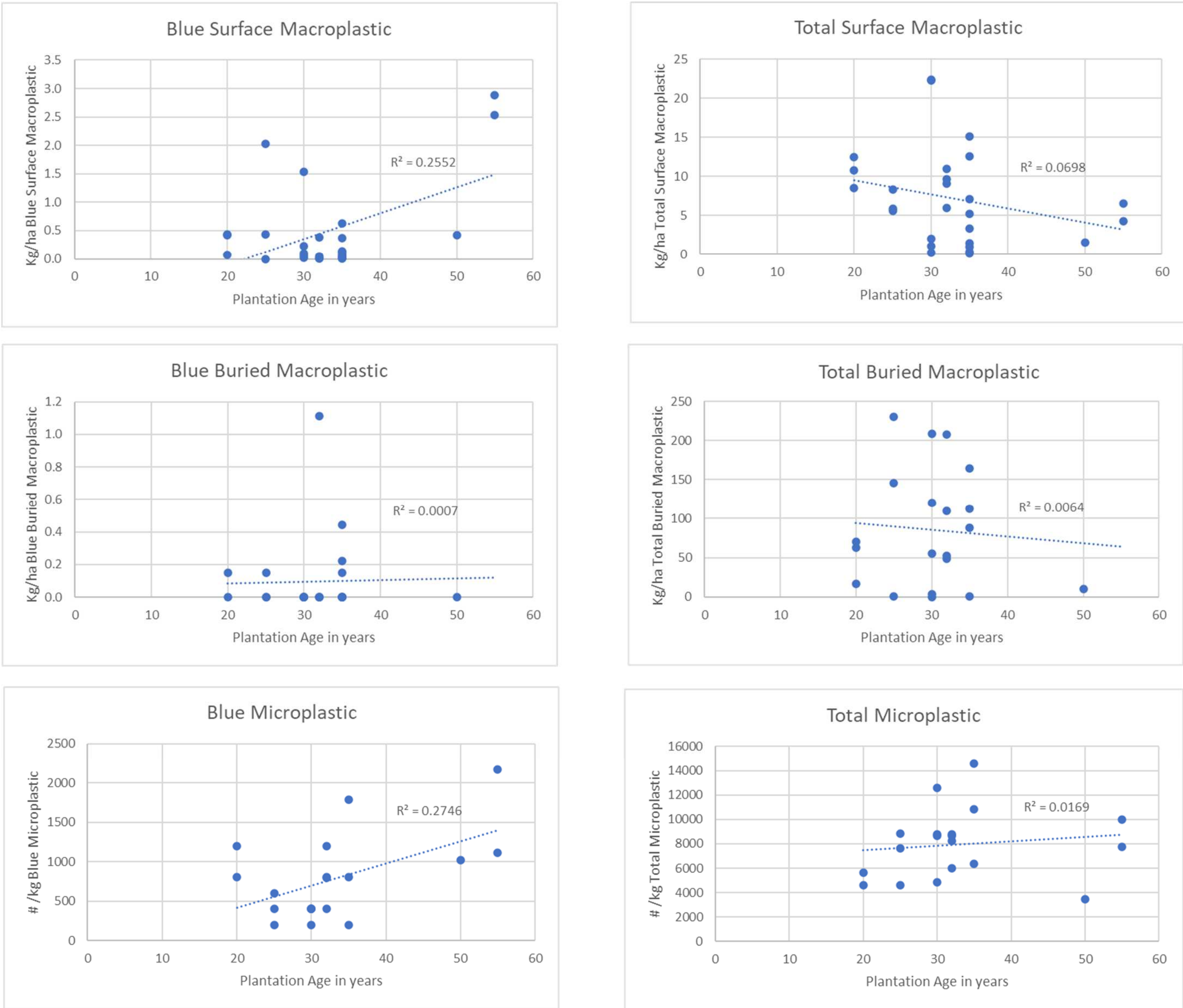

Figure 19: Graph overview of correlations between average values of different plastic categories and plantation age.

Both types of buried macroplastic have an outlier in their values, which might explain their poor correlation factors. However after removal of their respective outliers, their R^2 do not improve, for blue buried macroplastic the value becomes 0.0007 and for total buried macroplastic 0.0064 .

3.4.4 Replantation

The effect of replanted versus non-replanted is depicted in Table 5. Using T-tests. The only significant difference between the two groups was found for the total surface macroplastic, with a P-value of 0.00036. All other groups did not show any significant differences.

Table 5: T-test results of replanted versus non-replanted plantations, significant P-values highlighted in bold.

	Not replanted		Replanted		
	Average	Variance	Average	Variance	P-value
Blue Surface (Kg/ha)	0.35	0.27	0.63	1.03	0.39
Blue Buried (Kg/ha)	2.14	62.61	0.19	0.13	0.38
Blue Micro (#/Kg)	644.96	146972.24	909.74	413227.56	0.29
Total Surface (Kg/ha)	10.90	35.77	3.18	8.06	**0.00**
Total Buried (Kg/ha)	101.61	4972.75	128.12	47701.95	0.75
Total Micro (#/Kg)	7640.92	9555745.07	8198.44	7492943.44	0.68

3.5 Burial Tests

The initially implemented burial tests did not show any weight loss over a period of a little under 2.5 months. Weight before burial of the first bag was 3.13grams, after burial a weight of 3.335 was measured, higher than the initial value. Results of the second burial test will reveal themselves over time.

4. Discussion

4.1 Methods

4.1.1 Sampling locations

The plantations were chosen based on their age and soil type. However in hindsight the ages seemed to differ from the expected age. This led to an unfavourable distribution of age classes. As can be seen in table 1, most plantation ages were situated between 30-35 years. Which corresponds with a founding age of about 1990, exactly when recycling measures were being implemented in Costa Rica. A better screening for plantation ages would have been ideal, however in the case of this research there was really possible, since in the end the selected plantations were based on availability.

4.1.2 Microplastic measurements

The microplastic measuring methodology that was used in this study was based on input by several experts, yet initially it was a process of trail and error in order to determine the methodology that worked best. This trail and error process did take some time, and effectively reduced the amount of samples that could be analysed.

There are a few things that could have been improved in future research with the same methodology. One of which is the use of glass containers instead of plastic containers during the centrifugation process, to prevent contamination with microplastics. Furthermore the paper towels that were used to store the paper filter that included the microplastic samples contaminated the samples with some coloured material that was very similar to plastic. Creating confusion during the classification process. It would have been of great added value to have used micro-infrared spectroscopy to classify found particles with greater certainty.

The blank results of the microplastics were far from satisfactory. In the case of blue microplastic, the blanks had a higher average than the rest of the samples. This could indicate that cross-contamination has taken place during either the lab work, or storage. Future studies might look more into this.

The used subsample strategy of only sampling half of each filter paper proved to be accurate for the total microplastic found, however very large differences were found for the amount of blue microplastic material. The largest difference found had 0 blue microplastics in the subsampled, and 1193 blue microplastics when fully sampled. In hindsight this subsampling strategy was not ideal. Instead a randomized subsampling could have been used better, however this would not have not been as effective in reducing the amount of time needed per sample. The reason for introducing the subsample strategy was because of a lack of time to analyse all samples. If randomized subsampling was used, it would not have been possible for all samples to have been measured. Therefore this subsampling had its value, even though the results are less than ideal.

4.2 Results

4.2.1 Macroplastics

Most of the found macroplastic, either on the surface or buried, consisted of the polypropylene twine. Yet the usage of the plastic bags and the twine are roughly equal. This means that either, relatively speaking, more of the twine material is left in the field, and/or breakdown rates are significantly lower than that of the blue bag material.

4.2.1.1 Blue bag observations

Found blue bag macroplastic was often small, a complete bag was never found. This shows that collection of the blue bag plastic residue is done systematically by the plantation workers. This is also due to the fact that the bags are still around the banana bunches during the harvesting. Most pieces of blue bag macroplastic that were found were small disks left by incomplete perforation of the plastic bags or small pieces of blue bag that had been torn off (Figure 5).

Some of the blue bag material that was found in the field had already degraded into a brittle form that made collection almost impossible, as seen in figure 5. This was also seen in plantation V4, which is 20 years old. Therefore this deterioration has taken place within these 20 years maximum. Although this deterioration is not complete, it does show that the blue plastic residue is able to degrade within an overseeable timeframe. It is important to note that on the surface, photodegradation plays a strong role in this process. It is harder to make any statements on the role of the soil, and how fast buried (micro)plastic degrades.

Additionally there was only a very small percentage of bags that seemed in this further stage of degradation. This could have two reasons: the 'fresh' macroplastic accumulates, but it partially removed, either through flooding or collection by plantation workers before it reaches a state of further degradation. Another reason could be that the degradation curve of the plastic is non linear: meaning that it takes a long time for the plastic to start showing signs of degradation, but after that the process might disappear quite fast. This would be an interesting theory to test through the setup of burial tests.

4.2.1.2 Plastic twine observations

Plastic twine material that was found ranged from small pieces up to pieces with a length of a few meters. This is indicative that the emphasis of plastic residue collection by the plantation workers is more focused on the blue bag material, and less on that of the twine. It occurred quite often that the plastic twine material found on the surface was still bound to a stump of an already died-off plant. Because of this, the twine material would have firstly have to be cut loose before collection can take place. This could be one of the reasons more twine material is more likely to be left behind, since the collection is more time consuming than simply picking up the plastic material.

Twine material showed the most deterioration in plantation V5, the oldest of all sampled locations, giving the most time for the plastic to degrade. But it also is the only plantation where black twine was found, therefore it could also be that this type of twine plastic becomes brittle faster compared to their orange or blue counterparts. In plantation V1 some orange twine was found that lost some smaller particles when rubbed, although this was by far not as brittle as the material found in plantation V5. This shows that within 35 years, some degree of deterioration has taken place.

4.2.1.3 Macroplastic averages

From the given averages it would appear that blue buried macroplastic outweighs surface blue macroplastic 2:1, however the blue buried average value is strongly influenced by one outlier, and after excluding it blue surface macroplastic becomes far more prevalent. This does pose the question whether with more samples this average would still hold up. Since in the case of the total macroplastic, buried macroplastic shows much higher values (7.54 to 106.63 on average).

The higher total buried macroplastic might be explained by the fact that the polypropylene twine material seems to degrade much slower than the blue bags. Because of this most of the blue bag material is degraded while still on, or very close to the surface. While the Twine material has more time to reach deeper levels underground. It might also be explained by the fact that for the buried macroplastic a volume was measured instead of a surface. The extra dimension of depth gives more space for plastic to be found.

4.2.2 Microplastics

4.2.2.1 Microplastic observations

It is surprising that the found microplastics were mostly fibres. Generally speaking agricultural (mulching) films break down into fragments (Qi et al. 2020), and the breakdown of such material into fibres is not yet recorded. Still, when observing pieces of macroplastic under the microscope, it could be seen that at some of the edges fibre-microplastic was forming (Figure 10). In other instances the blue bag plastic did seem to break down into fragments (Figure 11). These fragments were rarely found back in the microplastic measurements. This could be due to misclassification, and not recognizing the fragments as being plastic.

Another interesting find is that the blue and orange microplastics seemed to lose their colour over time (Figure 12). This loss of colour means that transparent microplastics found could also have been of the same origin as the blue microplastics. However it was not possible to determine this by eye alone.

Contrarily to the macroplastics, one study regarding microplastics in banana plantation soils was found. Xu et al. 2022 studied microplastic contamination under different land uses in south western China. One of these land uses was a banana plantation, about fifteen years of age.

There are striking differences between our study and Xu et al.'s. In our study, 12% of found microplastic is blue of colour, and 56% is transparent. In the study of Xu et al 2022, 60% of the found microplastics are blue of colour, with only 2% being transparent. Additionally, more than 95% of found microplastics were fragments, with less than 5% being fibres. This could suggest that the plastics found were of a different origin, or have different characteristics. It could be possible that the blue plastic bags that are used in China differ chemically from the ones used in Costa Rica.

Xu et al.'s study does not mention the colour of the twine material that was used. But it does mention that 10.9% of found microplastic was polypropylene. If we are to assume that the red microplastics found in our study correspond with the polypropylene twine, our study finds double the amount, 22%. However it is not at all sure whether all found red microplastics are polypropylene, therefore these numbers cannot directly be compared to each other.

4.2.2.2 Microplastic Averages

Xu et al (2022) Found 10975.0 ± 261.0 particles per kg in the top 20 centimetres of soil in a 10-20 year old banana plantation in south western China. Of which 15,600 ± 463.7 particles per kg was in the top 10cm and 6350 ± 907.0 particles per kg in between 10-20cm. These are relatively numbers compared to other land uses in China and across the world (Xu et al. 2022; Sa'adu & Farsang; 2023). Most studies on agricultural soils find much lower values, However there are also quite a few studies that find much higher numbers. These studies are often related to the use of waste water or sludge (Tagg et al. 2022; Liu et al. 2018). One of reasons for the relatively high microplastic content given by the paper of Xu et al 2022 is the fact that the soil in banana plantations receive a lot of sun light and a lot of concentrated rainfall due to the 'funnel shaped' pattern of the banana leaves. This leads to an increased rate of mechanical abrasion of macroplastics and a faster formation of microplastics (Zhang et al. 2021a).

In our study we found 7720.1 ± 2809.0 total particles per kg on average, over a depth of 15 cm. This a lower amount than the found in China. This can have several explanations. Although there's no specific information available on how plastics were disposed in this or other Chinese banana plantations, it seems that recycling of agricultural plastics still is a developing process in these regions (Liu et al. 2014). Therefore one would not automatically expect similar amounts of plastics in a Costa Rican plantations of this age. Still, this study also find relatively high numbers of microplastic compared to other studies in agricultural soils (Xu et al. 2022; Sa'adu & Farsang 2023).

However, it is important to notice that differences in methodology of microplastic analysis are very important, and can lead to a degree of incomparability of studies (He et al. 2018). In the study of Xu et al 2022, A different density solution was used, of 1.6 gram cm^-3. And their filter paper had a pore size of 5μm. In this study, the solution density was 1.13 gram cm^-3 and the pore size 11 μm. This means that in Xu et al.'s study both denser and smaller microplastics were accounted for compared to our study. Additionally, Xu et al 2022 used Micro-infrared spectroscopy to verify whether the found particle was made of plastic or other material (Schymanski et al. 2021). In our study it was less certain whether seen particles were correctly categorized as plastic, or non-plastic.

4.2.3 Correlations

The correlation between the different measured plastic classes in none of the cases considered strong. A major reason for the lack of strong correlations could be the fact that there are not enough samples taken in order to have more precise results for each of the classes. If more samples could have been taken stronger correlations might have been found.

The strongest correlation is for Total surface – Total buried macroplastic, after the removal of one outlier. The most occurring plastic type for both these categories is the polypropylene twine material. Since before being buried, the macroplastic first has to end up on the surface makes the correlation between the two categories to be expected.

4.2.4 Explaining factors

The influence of soil types can only be seen on the amount of blue surface macroplastic (Table 3). The soils of non-volcanic origin have a significantly higher amount of blue surface macroplastic than soils of volcanic origin. This could be explained by the fact that the soils of volcanic origin are more prone to compaction and therefore have a stronger degree of surface runoff. The blue bag material is lighter and thinner than the other types of plastic, making it more possible for the material to be carried along with surface flow currents.

Grass cover only had a significant effect on the total surface macroplastic (Table 4). A possible explanation for this could be that the macroplastic got overgrown, and was therefore either harder to spot while searching the surface, or easier buried by soil material that accumulates between the vegetation. A P-value of 0.09 was found for the influence of grass cover on blue microplastic. However the fully covered soils shows higher blue microplastic than the half covered soils (Table 4). This does somewhat debunk the theory that the level of coverage could have an impact on the abundance of blue microplastic. However one could expect grass coverage to positively influence microbiological activity, and therefore biodegradation of the microplastics. Therefore it would be interesting to research this in more detail in follow-up research.

The correlation between the plantation age and plastics can be seen for blue surface macroplastic and blue microplastic (Figure 19). Although the correlations are still considered weak they do show some effect of age. Which would be expected when the plastic keeps on accumulating. Interestingly, the total surface macroplastic does not follow this trend, and even shows a negative correlation with plantation age. However, it does show a strong, significant relationship with being replanted or not (Table 5). The plantations with the highest plantation age have all been replanted, which offers a possible explanation of the negative correlation for the total surface macroplastic. This does however not explain that the correlation for the blue surface macroplastic remains positive.

4.2.5 Burial test

The performed burial test showed no weight loss for blue bag macroplastic after 71 days. As a matter of fact, the measured weight even slightly increased. This is probably due to a difference in cleanliness after washing the plastic material. Some impurities might have still been left after cleaning the plastics. The burial test should have lasted longer in order to see any results. This does not mean that absolutely no deterioration has taken place. Degradation of plastic does not always have to be associated with weight loss (Zhang et al. 2021b). In order to account for inaccuracies, the follow up version of the burial test is done in triplicate. This burial test will also last for a longer timeframe.

5. Conclusions

Averages of 0.44±0.77 for surface-, and 1.18±5.69 kg per hectare for buried blue macroplastics were found. The average total macroplastic found was much higher with 7.54±6.76 for surface-, and 106.63±139.55 kg per hectare for buried total macroplastic. Most of the found macroplastic material was polypropylene twine. As for microplastics, average values of 775.9±512.9 and 7720.1±2809.0 particles per kg were found for blue-, and total microplastic respectively. These results are lower than those found in a banana plantation in southwestern China. Still, these differences have to be viewed with care, since the methodologies are not equal, which can have a strong influence on the results.

All correlations between the measured plastic categories proved to be negligible. However, some influences of explaining factors have been found. The soils of non volcanic origin had a significantly lower blue surface macroplastic content, which could be explained by the compactability of the soil, which increases the chance of flooding and runoff by rainwater. A higher grass coverage made for a significantly lower total surface macroplastic content. This could be explained by the fact that it was harder to spot surface macroplastic and burial of the plastic might easier take place. The age of the plantations is, although weakly, positively correlated with both found blue surface and blue microplastic amounts. While the act of replantation significantly lowered the amount of total surface macroplastic found.

The degradation rate of plastics proved to be difficult to assess. A burial test of 71 days gave no weight loss for blue bag macroplastic. However, From field observations it was found that the blue bag macroplastic showed fragmentation within 20 years, to the extend it was not possible to touch without breaking it. The twine material only showed decolouration within 30, and some degree of fragmentation within 35 years time. No nearly-decomposed twine material was found, suggesting a lifespan of at least 60+ years.

To answer the main research question, a better, and more distinct distribution of old- and new plantations would have been needed. However the efforts of collecting and recycling can be clearly seen within the fields. Additionally the research of Lieben (2023), who focussed on blue bag contamination of Costa Rican rivers and beaches, found no blue bags during their sampling. And through interviews it was determined that although the amount of plastic residue in rivers and on beaches used to be very high, this is barely the case anymore.

However, this research shows that improvements are possible. Mainly in the form of collection of the polypropylene twine material. It offers another chance for the Costa Rican government to stay ahead of the curve in terms of sustainability within its agricultural practices.

Additionally, the banana plantations show a great potential as case study on the topic of microplastics in the soil. This due to the possibility of studying the effects of time by sampling different plantations of different ages. Because of the increasing public awareness and concerns, need for microplastic research is higher than ever. Researching microplastics within the banana plantations offers great chances to answer some of the many questions regarding the effects of microplastics for the health of crops and of the environment.

6. Recommendations

Both the subsampling inaccuracy and the high values of blank measurements indicate that the microplastic values measures not as accurate as we would have wanted. More accurate results could have resulted in clearer relationships between other plastic classes or explaining factors. A recommendation for next time would be to take extra care to prevent cross contamination during from taking place, for instance by storing samples in glass petri dishes, instead of between paper towel. Additionally, the usage of near-infrared spectroscopy greatly helps in the correct classification of plastic particles and is therefore strongly recommended.

The emphasis of collection and recycling of plastic material seems to mainly focus on the blue bag plastics. However, this study shows that some of the larger twine material is sometimes still left on the field. This study shows that the twine material has a much slower breakdown rate and is likely to accumulate into great amounts within the soils of banana plantations, if proper collection does not take place. We think this is an opportunity for the Costa Rican banana industry to, once again, take a leading role within environmentally-friendly management practices. Showing a proactive attitude towards this problem of plastic in the environment to the rest of the world might popularize, and raise the value of the Costa Rican banana compared to bananas from other production systems.

Microplastics are very much a trending topic within science, and public concerns about their potential dangers higher than ever. The banana plantations might make for an excellent case study on the topic of microplastics. This study find high numbers of microplastic compared to other studies in agricultural soils. These results were spread throughout different plantations, with a very similar production system, Few management aspects differ between plantations, making comparability relatively easy, which is an important aspect within research. Yet, ages of plantations differ and therefore also the amount of plastic that potentially entered the system. Because of this, the effects of time can be measured throughout the different plantations.

Not only is it important to understand whether microplastics form a threat for the banana plant in terms of production, but the case study of microplastics in banana plantations might also help understand the effects and workings of microplastics within soils in a more general sense. Interesting research questions could be whether the microplastics have any effect on the rhizosphere of the plants, and whether any uptake by the plants take place. Additionally, the effect of soil microbial activity on the abundance, and breakdown, of the microplastics could be assessed within these plantations. Answering these questions could help the scientific community to better understand and deal with the problem of accumulating numbers of microplastics.

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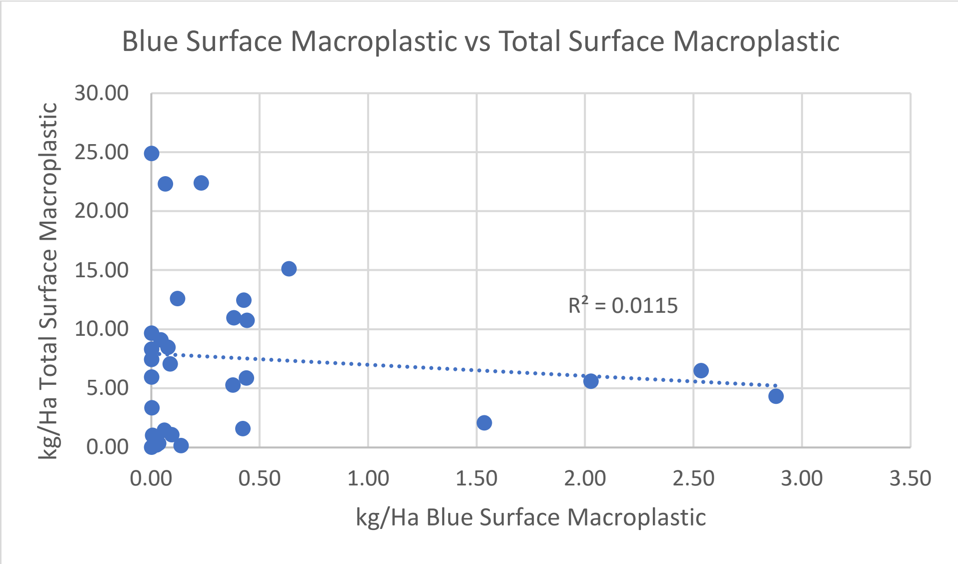
8. Appendices

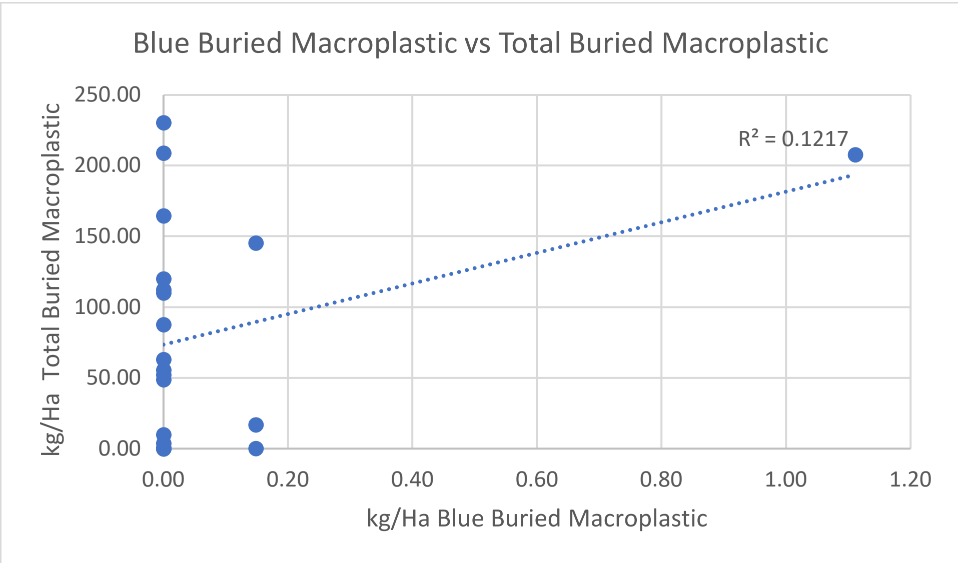
Appendix 1: Overview of initiated burial tests

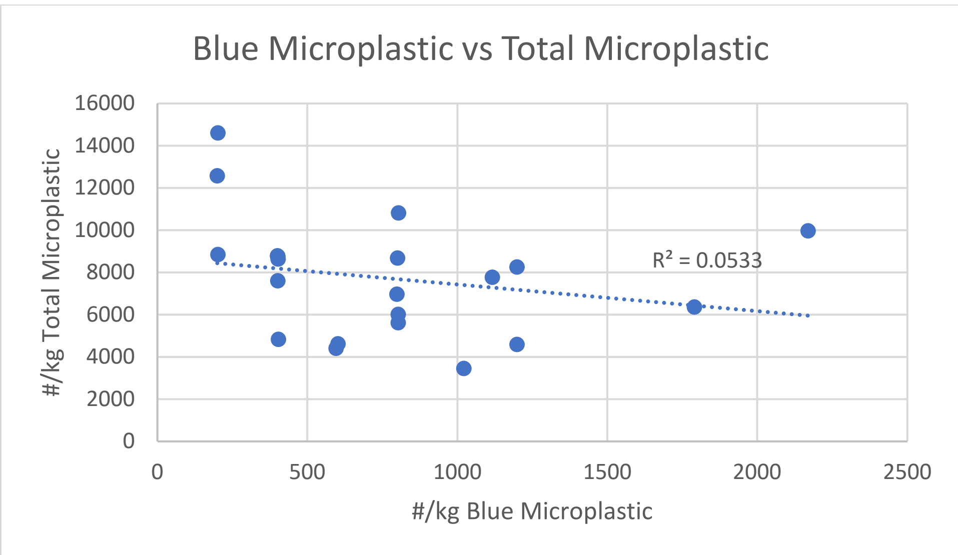
	Start date	End Date
Experimental Farm Corbana	**15-11-2022**	**25-01-2023**
Seed bank Corbana	**26-01-2023**	**26-01-2024** **26-01-2025** **26-01-2026** **26-01-2027**

Appendix 2: Correlation factors between the different plastic classes

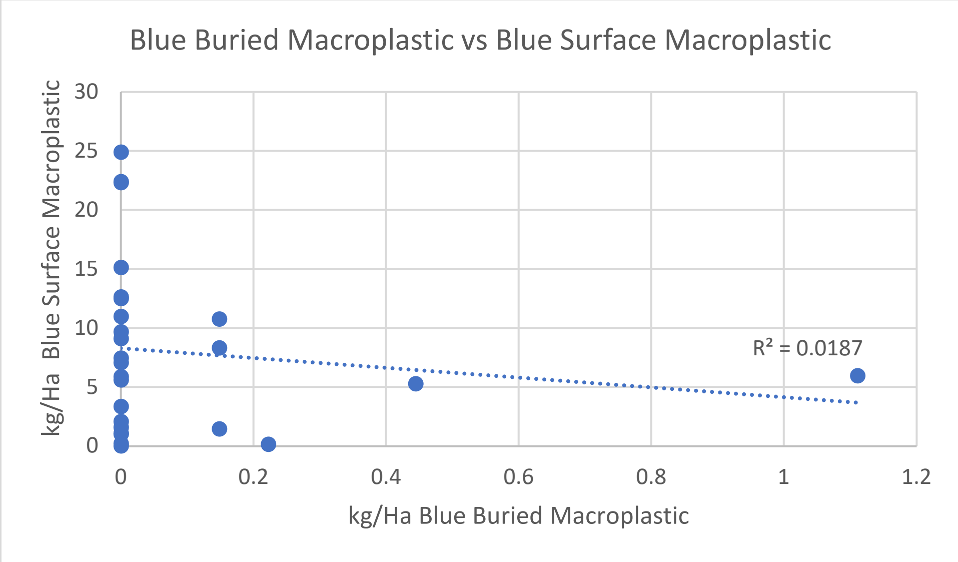
Blue versus total plastic categories:

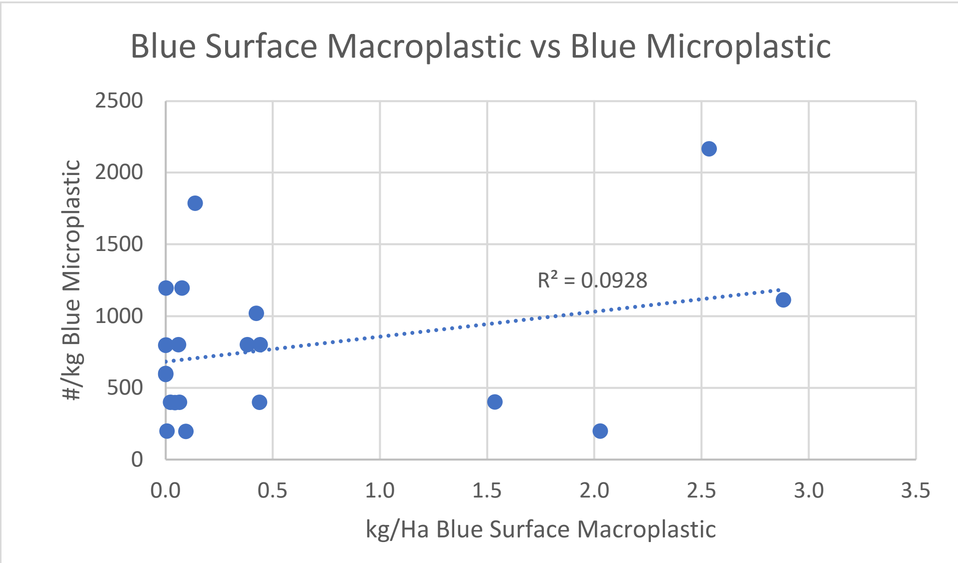


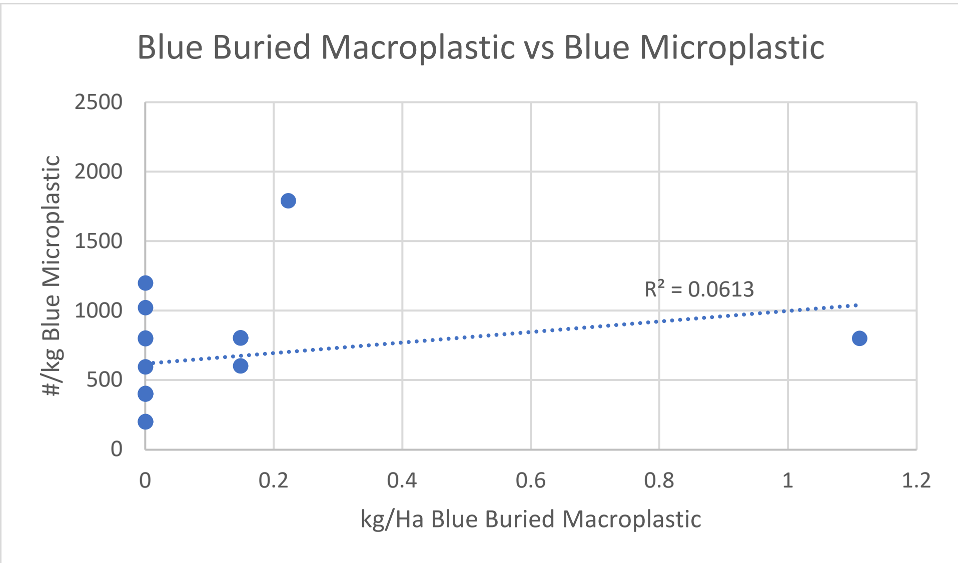




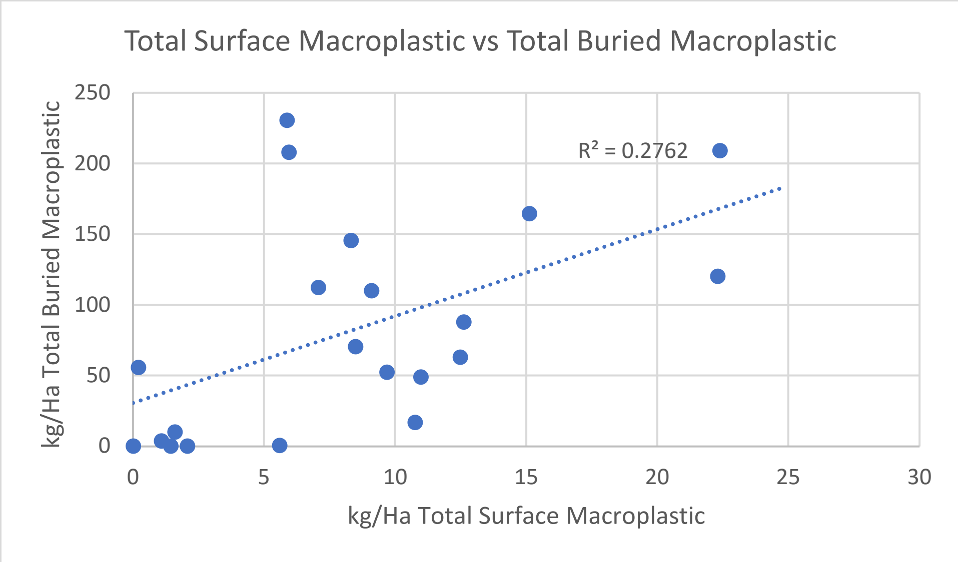
Blue plastic categories:

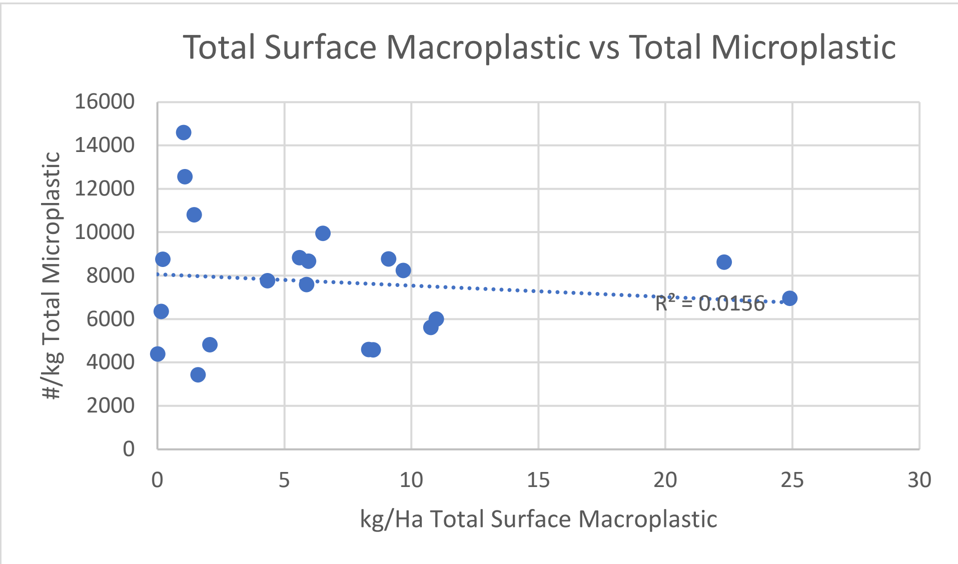


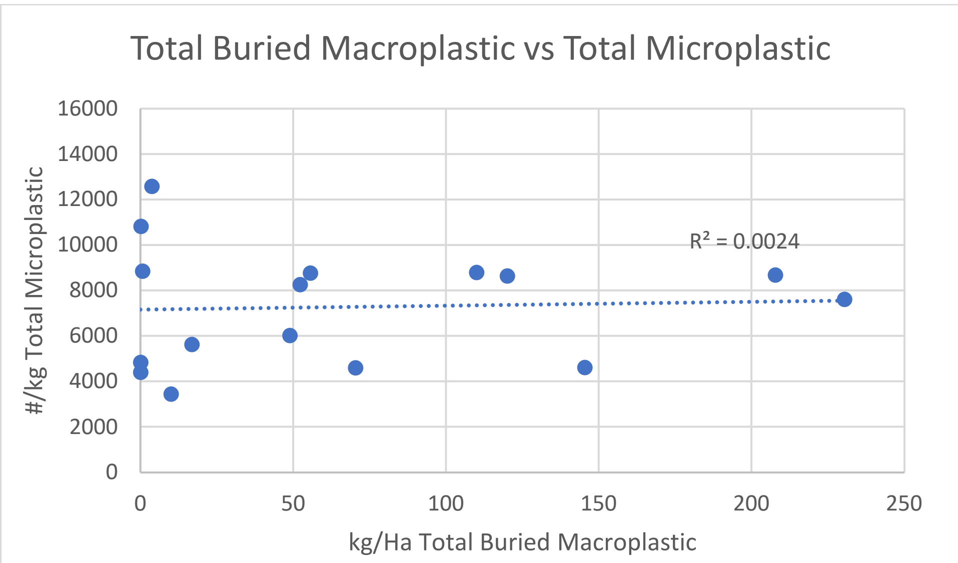




Total Plastic categories:







Appendix 3: T-test results of soil type differences without Abandoned plantations

Blue Surface		
	Non-Volcanic	*Volcanic*
Mean	0.931	0.176
Variance	1.207	0.041
P two-tail	**0.048**	

Blue Buried		
	Non-Volcanic	*Volcanic*
Mean	0.016	2.114
Variance	0.002	58.031
P two-tail	0.304	

Blue Micro		
	Non-Volcanic	*Volcanic*
Mean	691.1	887.9
Variance	366397.1	218237.5
P two-tail	0.436	

Total Surface		
	Non-Volcanic	*Volcanic*
Mean	7.291	7.106
Variance	61.734	23.081
P two-tail	0.945	

Total Buried		
	Non-Volcanic	*Volcanic*
Mean	86.049	130.951
Variance	8598.359	28901.131
P two-tail	0.449	

Total Micro		
	Non-Volcanic	*Volcanic*
Mean	7703.8	8190.5
Variance	7554834.3	9529880.3
P two-tail	0.723	