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AGROCHEMICAL RETENTION AND TRANSPORT THROUGH LEACHING AND SURFACE RUNOFF IN A BANANA PLANTATION

Determination of the factors affecting agrochemical losses in a banana plantation in the northern Caribbean lowlands of Costa Rica, by using potassium as a proxy method.

By Jolien Lelivelt
940628510120

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Wageningen UR
Supervisors: dr. ir. Jetse Stoorvogel
& Rafael Segura Mena, MSc

Abstract

Commercially grown bananas are among the world's most pesticide intensive crops, the plantations are frequently found upstream of, or adjacent to, vulnerable ecosystems. Understanding water flows in the system gives insight in the behaviour of agrochemicals and also reveals through which ways agrochemicals leave the system, given that agrochemicals are (mostly) conveyed through water. The objective of this thesis is to study potassium retention and transport through leaching and surface runoff in order to determine the dominant water trends in the system. Three potassium treatments were applied in the banana plantation "San Pablo" located in Limón, Costa Rica: 457, 540 and 623 kg K ha^{-1} yr^{-1} .A lysimeter experiment was carried out to assess the influence of these various fertilizer quantities on potassium leaching in both the band and inter row position. The (tertiary) drainage system has also been sampled in order to distinguish between potassium loss by nutrient leaching and surface runoff. Potassium concentrations (in mg/L) in the water samples were determined by the use of spectrometry. The study showed that the main potassium losses in San Pablo are caused by surface runoff. The base flow dominates most of the time, resulting in potassium concentrations of 1.3, 2.3 and 2.9 mg/L on average, in the channels of the control treatment, treatment 1 and treatment 2. The study rules out the possibility that a major part of the applied potassium is lost through deeper leaching, since the potassium concentration in soil moisture at 120 centimetre depth amounts on average 0.73 mg/L (band), and even less at the inter row position (0.64 mg/L). The extreme outliers measured in the tertiary channels, emphasize the expected potassium losses by surface runoff. The biggest losses are suffered either during intense precipitation and/or right after fertilizer application. If no point source pollution takes place, no serious water quality problems occur in vulnerable ecosystems downstream the banana production zone of Costa Rica.

Abstracto

Las bananas cultivadas comercialmente se encuentran entre los cultivos más intensivos en pesticidas del mundo, las plantaciones se encuentran con frecuencia aguas arriba de, o adyacentes a, ecosistemas vulnerables. La comprensión de los flujos de agua en el sistema da una idea del comportamiento de los agroquímicos y también revela a través de qué formas los productos agroquímicos abandonan el sistema, dado que los agroquímicos son (principalmente) transportados a través del agua. El objetivo de esta tesis es estudiar la retención y el transporte de potasio mediante lixiviación y escorrentía superficial para determinar las tendencias dominantes del agua en el sistema. Se aplicaron tres tratamientos de potasio en la plantación de banano "San Pablo", Limón, Costa Rica: 457, 540 y 623kg K ha-1 año-1. Se realizó un experimento de lisímetro para evaluar la influencia de estas cantidades de fertilizante en la lixiviación de potasio tanto en la banda como en la posición entre hileras. El sistema de drenaje (terciario) también ha sido muestreado para distinguir entre la pérdida de potasio por lixiviación de nutrientes y la escorrentía superficial. Las concentraciones de potasio (en mg / l) se determinaron mediante el uso de espectrometría. El estudio mostró que las principales pérdidas de potasio en San Pablo son causadas por la escorrentía superficial. El flujo base domina la mayor parte del tiempo, resultando en concentraciones de potasio de 1.3, 2.3 y 2.9 mg / L en promedio, en los canales del tratamiento control, tratamiento 1 y tratamiento 2. El estudio descarta la posibilidad de que una gran parte del potasio aplicado se pierda por lixiviación más profunda, porque la concentración de potasio en la humedad del suelo a 120 centímetros de profundidad equivale a un promedio de 0,73 mg / L (banda), y en la posición entre hileras incluso menos (0.64 mg / L). Los extremos atípicos medidos en los canales terciarios enfatizan las pérdidas de potasio esperadas por la escorrentía superficial. Las mayores pérdidas se sufren durante la precipitación intensa y / o inmediatamente después de la aplicación de fertilizantes. Si no se produce contaminación de fuentes puntuales, no se producen graves problemas de calidad del agua en ecosistemas vulnerables aguas abajo de la zona de producción bananera de Costa Rica.

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1. Introduction

Costa Rica has a wealth of biological diversity. Holdrige & Grenke (1971) list a range of ecosystems which exist in the country, including 12 different life zones ranging from tropical dry to tropical wet to tropical sub-alpine. The country contains 5 percent of the world's biodiversity within just 0.035 percent of the earth's surface (Honey, 1999), lowland forests of the tropics are the most species rich of all terrestrial ecosystems (Turner, 1996). Although many of the forest, mangroves, marshes and coral reefs are protected, surrounding lands are not (Worobetz, 2000). Another integral part of Costa Rica's land use and economy is the production of bananas (*Musa acuminata*), pineapples (*Ananas comosus*) and potatoes (*Solanum tuberosum* L.), plantations are frequently found upstream of, or adjacent to, vulnerable ecosystems (McCracken, 1998). Pineapple- and banana farms are mainly located in the Caribbean zone, where the temperature, rainfall and rich alluvial soils are suitable for the large scale production of the tropical fruit (De La Cruz Medina & Garcia, 2005; Mccracken, 2011). Bananas do have a high water demand and 25 mm/week is regarded as the minimum for satisfactory growth (Yara.in, 2018). One can find the potato fields at altitudes varying between 1500 and 2100 meter above sea level (Montero-astúa et al., 2008). In 2016, a total of 2.9 million tonnes pineapples and 2.4 million tonnes of bananas were produced (FAOSTAT 2016), where the potato production in Costa Rica is lower, and amounted 62.000 tons in 2014 (MAG, 2014). The majority of the pineapple and banana production is being exported, potatoes are consumed locally (FAOSTAT).

Large-scale, monoculture banana production systems in Costa Rica depend on agrochemicals, due to the naturally high nutrient demand of the plant (Robinson & Saúco, 2010). The systems are vulnerable for diseases, since bananas are perennial plants which grow in perhumid conditions (Clay, 2013). Approximately 45 kilograms of active ingredients per hectare per year are used in Costa Rican plantations (Bravo-Durán et al., 2013; Castillo et al., 1997; Castillo et al., 2000; Ramírez et al., 2009). In 2000, Costa Rica ranked second in the world regarding to pesticide use (World Resources Institute, 2007). In comparison, only 11.6 kg of active ingredient per hectare per year are used in the Dutch Ware-potato industry (De Jong & De Snoo, 2002). The large total application is applied though split application, to prevent rapid losses due to surface runoff and leaching as a result of high rainfall intensities. More than 15% of farm management costs is spent on such chemicals (Stoorvogel et al., 2004).

Due to high precipitation rates is irrigation unnecessary in Costa Rican banana plantations, and on the contrary, a complex system of primary, secondary and tertiary drains have to be installed. All agrochemicals (fertilizers, pesticides, fungicides and herbicides) are conveyed through water (Kennedy et al., 2000). A part of the applied agrochemicals are leached into the groundwater or end up in the drainage system by surface runoff losses. Agrochemicals remain in the system for extended periods and ultimately enter marine environments. In the tropics, agrochemicals that do reach the coast can be trapped and accumulate in mangrove swamps and coastal waters (Henriques et al., 1997). Despite the fact that concern exists that the banana production systems negatively affects (marine-) ecosystems downstream from the plantations (Clay, 2013), this has never been proven. Most agrochemicals are hard to follow in the system and are hardly traceable due to relatively low concentrations, caused by dilution (NPIC).

Understanding water flows in the production system gives insight in the behaviour of agrochemicals and also reveals through which ways agrochemicals leave the system, given that agrochemicals are (mostly) conveyed through water. Effective management on agrochemical use will lead to economic benefits, by reducing expenses, and ease the pressure on the ecosystems downstream. Potassium measurements may be used as a proxy method to investigate the flows of agrochemicals in these system. Potassium dissolves easily in water, therefore, the only possible system outlets (except from the harvesting of bananas of course) are leaching and surface runoff via surrounding streams. At larger scales, using potassium as a proxy allows to distinguish the effects of banana plantations from other industries (e.g. pineapple), the nutrient is used in the banana industry only in these large amounts. The objective of this paper is to study potassium retention and transport through leaching and surface runoff in order to determine the dominant water trends in the system. The following research question with associated sub questions have been formulated:

Which factors affect potassium losses in a banana plantation in the northern Caribbean lowlands of Costa Rica?

- What are the effects of hydrological processes on the potassium losses in a banana plantation in the northern Caribbean lowlands of Costa Rica?
- What are the effects of fertilization practices on the potassium losses in a banana plantation in the northern Caribbean lowlands of Costa Rica?

2. Theoretical background

The extent of potassium loss and the pathways of these losses are a function of several factors and processes; hydrological factors, plant physiology, soil type and management practices. Some processes increase potassium losses, some cause a reduction. The various processes can reinforce or attenuate each other. In order to understand the behaviour of nutrients in the banana cultivation system, the complex hydrological system is explained in this next section

2.1 Hydrological processes in a banana cultivation system

Precipitation is the only form of water addition to the system, a part reaches the soil directly, the majority of the precipitation is intercepted by the plant canopy. The intercepted water either evaporates from the canopy or reaches the soil by stem flow and through fall. The precipitation that reaches the soil, will either infiltrate or causes saturated overland flow (Sevenhuysen & Maebe, 1995). This ratio depends on both precipitation duration and intensity and the infiltration capacity of the soil. Schosinsky (2006) states that soil texture has most influence on the infiltration capacity. A common practice in banana plantations is to leave plant residues on the soil surface after harvest and during deleafing and desuckering. Nutrients from the plant residues are hereby recycled, but this also affects the hydrological processes in the plantation. Soil erosion, inhibited water runoff, and prevention of surface sealing are consequences of the management practice (Cattan et al., 2006). Also, the leaves reduce the soil surface where infiltration can occur.

Due to saturated overland flow, the dissolved nutrients leave the system immediately through the drainage system. The remaining water will infiltrate and percolate downwards. This water will be taken up by the banana plant from the unsaturated root zone and transpire, will be stored in the soil (on the long term the amount of storage equals zero) or will move towards the zone below the roots. The transpiration term consist of soil evaporation, evaporation of the canopy and respiration of the plant. Thisratio depends on characteristics of the atmosphere, the soil and vegetation. When the water is beneath the root zone, the nutrients dissolved in the water are considered as lost, this process is called leaching. The distribution between nutrient losses caused by runoff and leaching highly depends on the intensity of rainfall events. C effects may also occur. For example, high rainfall intensities will cause surface runoff, this would result in higher nutrient concentrations in the drainage systems. However, this process is inhibited by the fact that high rainfall intensities dilute.

The impluvium shape of the canopy redistributes rainfall considerable (Bussière, 1995). The main pathway for redistributed rainfall is, according to Cattan et al. (2007b) by stem flow (18-26%). Stem flow causes a water load on the soil of 20- to 28-fold higher at the plant collar than the actual rainfall rate. Also, dripping points (through fall) provide locally high water loads on the soil, up to five-fold higher than the initial precipitation rate. Due to the redistribution of rainfall, local water loads could exceed the soil infiltration capacity, which favours surface runoff. This redistribution also enhances the percolation fluxes in the and thereby fast leaching of nutrients near the pseudo stem soil (Cattan et al, 2007b; Sansoulet et al., 2007). Given that fertilizers mostly are applied at the base of the banana plant, the redistribution of rainfall will strongly affect nutrient leaching.

3. Materials and Methods

3.1 Study area

The study was conducted from the 1st of March until the 13th of June (104 days) in the northern Caribbean lowlands of the Limón province, Costa Rica, in an important banana producing area. In 2018, from the 2nd of March until the 30th of April the tertiary channels have been sampled. A lysimeter experiment has been carried out from the 19th of April until the 13th of June. The field experiment was located in the 254 hectares commercial banana plantation "San Pablo" (10°06'40.1"N, 83°22'53.3"W). The farm is divided in plots of approximately 60 by 20 meters (1200 m^2). The farm contains plants of the cultivar "Grande Naine", the cultivars of *Musa acuminata*, the plant density is roughly 2100 plants per hectare. The plots contain a slope of ±2.45% from the middle of the field towards the tertiary channels (Soto, 2013), this type of dome constructions promotes water drainage. The plantation has throughout the year a continuous production and exported over 48 tonnes per hectare in 2015 (Corbana, 2016).

The plantation is owned and managed by Corbana (Corporación Bananera Nacional) and is therefore available for research purposes. Data on harvest, fertilization, pesticide use and soil conditions was accessible via the cooperation. Climate data in this study was obtained from meteorological station "28 Millas" (Banaclima), located ± 1 kilometre from the study plots.

3.2 The potassium balance method

A common used method for estimation of nutrient losses in agricultural systems is the balance method (i.a. Bindraban et al., 2000; Sansoulet et al., 2007; Vosselen et al., 2005). The balance method is a statement of the law of conservation of mass, and simplifies the complex system of a banana plantation. Inflow equals outflow plus the change in storage. The amount of nutrient loss (in this case kilograms of potassium per hectare), by surface runoff (Q) and leaching (L) can be approximated by the nutrient balance:

$$Q + L + U = F + P + R \tag{1}$$

where U(=H+R) consists of H, the amount of potassium permanently removed by the system by product harvest (kg ha^{-1}), in this case by fruit removal and R, the crop residues of cultivation. Beside, F is the amount of potassium added to the system by fertilization (kg ha^{-1}) and P is the amount of potassium added to the system by precipitation (kg ha^{-1}). The soil storage term is ignored, since change in potassium storage over longer periods equals zero. The crop residues of cultivation (R) are left behind in banana plantations, and are not abstracted from the system. This means that this term can be cancelled out on both sides of the formula:

$$Q + L = F + P - H \tag{2}$$

In chapter 4.1 an estimate of the potassium loss due to surface runoff and leaching is made for San Pablo, using the potassium balance above.

3.3 Experimental set-up and treatment design

In order to determine the effects of hydrological effects and management practices on actual potassium losses, an experiment with 3 varying potassium fertilization treatments has been executed, in duplicate. In San Pablo is annually approximately 550 kg K_2O applied per hectare, spread over 17 applications (control measurement), this equals 457 kg potassium. Additional doses (KCl) are applied twice per year obtain concentrations of 540 and 623 kg potassium per hectare per year respectively. Later in the text, reference is made to these treatments as follows; the control treatment (457 kg K ha^{-1} yr^{-1}), treatment 1 (540 kg K ha^{-1} yr^{-1}) and treatment 2 (623 kg K ha^{-1} yr^{-1}). Each treatment was applied to two plots, one of each located in the western side of the plantation and another in the east. The fertilizer is not applied evenly on the soil, but only in a narrow band close to the young shoot of the banana plant.

3.4 Water sampling

The lysimeter experiment was carried out over 55 days to assess the influence of fertilizer quantities on potassium leaching. Each plot contains 2 lysimeters, one was installed in the fertilizer band around the foot of the pseudo stem at 120 cm depth, the other lysimeter was installed between two rows of banana plants (inter row), equally deep. The two different positions were chosen to account for the heterogeneity of the rainfall distribution, spatial variations in soil infiltrations due to agricultural practices (e.g. planting techniques) and the heterogeneity in the distribution of fertilizer application (Cattan, 2006; Sansoulet, 2007).

Suction lysimeters collect pore water from unsaturated soils (Figure 1). Vacuum was applied up to 300 mbar to the lysimeter by a hand pressure pump (TB-075), for moist soils the optimal vacuum (“Suction Lysimeters,” 2018). The negative air pressure inside the lysimeter draws the soil moisture into the lysimeter through its porous bottom. The soil moisture was transported to the surface once per week, by applying negative pressure to the lysimeter through the tube. The ground water was collected in an Erlenmeyer flask at the surface. Ground water samples were taken irregular in singular, respectively 66 samples were taken in total. All samples were taken between 09:00 and 11:00 local time (UTC – 6).

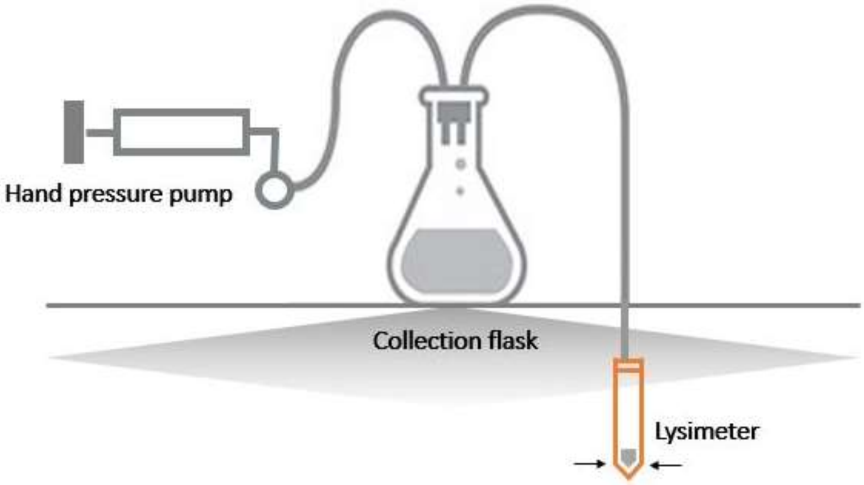

Figure 1 Simplified measurement set-up of the lysimeter experiment, based on Soil Measurement Systems (“Suction Lysimeters” 2018) .

The tertiary drainage system has also been sampled, this in order to distinguish between potassium loss by nutrient leaching and surface runoff. Water samples of 250 ml were taken irregular from the tertiary channels in triplicate, respectively 135 samples were taken in total. Tertiary channels often ran dry, this necessitated a well. The depth of the well amounted ±30 centimetre and was located approximately 15 meter from the secondary channels. Water samples were only taken when sufficient water was available and when the quality was sufficient in relation to turbidity.

Both the groundwater samples and the water samples from the tertiary channels were analysed in the laboratory from CORBANA, potassium concentrations (in mg/L) were directly measured in ICP/OES Optima 7300 DV (Inductively coupled plasma - optical emission spectrometry*)*. ICP/OES is a technique in which the composition of elements in (mostly water-dissolved) samples can be determined using argon plasma and spectrometry ("ICP-OES". (z.d.).

3.5 Data analysis

The differences in potassium concentrations between treatments (control, treatment 1 & 2) were tested by use of T-tests (P(T<=t) one-tail), in both soil moisture and tertiary channel water. Equal or unequal variance was assumed based on the Two-sample F-test for variances. In order to determine the mean difference between the tertiary channel samples (control treatment) and the calculated potassium concentration based on the nutrient balance, also a one sample T-test was used (P(T<=t) one-tail). Besides, the concentration differences between the band and inter row position were tested with a T-test (two-tailed).

4. Results

This paragraph aims to give insight in the distribution of potassium in the banana plantation, caused by the hydrologic functioning and fertilization practices. In chapter 4.1 an estimate of the potassium loss due to surface runoff and leaching is made for San Pablo, using the potassium balance. Thereafter (chapter 4.1.1), the nutrient balance of the control treatment will be compared with the two other treatments of the field experiment, where either 540 kg K (treatment 1) or 623 kg K (treatment 2) is applied per hectare on annual basis. This, in order to examine the impact of different fertilizer quantities on potassium distribution. Subsequently, the actual measured losses in both the tertiary drainage channels and the soil moisture are addressed in chapter 4.2, as well as compared with the estimated losses by the potassium balance .

4.1 The potassium balance

In the materials and methods section (chapter 3.2) is stated that the potassium loss (in kilograms per hectare), by surface runoff (Q) and leaching (L) can be approximated by the simplified potassium balance (formula 2). The potassium losses by surface runoff and leaching are dependent on the nutrient concentration in the water. This concentration is controlled by both the potassium and water availability at a specific time and location. From the 2nd of March until the 30th of April (60 days) approximately 300 mm of precipitation fell in total (Figure 2). The maximum rainfall intensity measured was 41 mm/h for events lasting 5 minutes (30-04-2018) and more than 13 mm for events lasting 60 minutes (24-03-18).

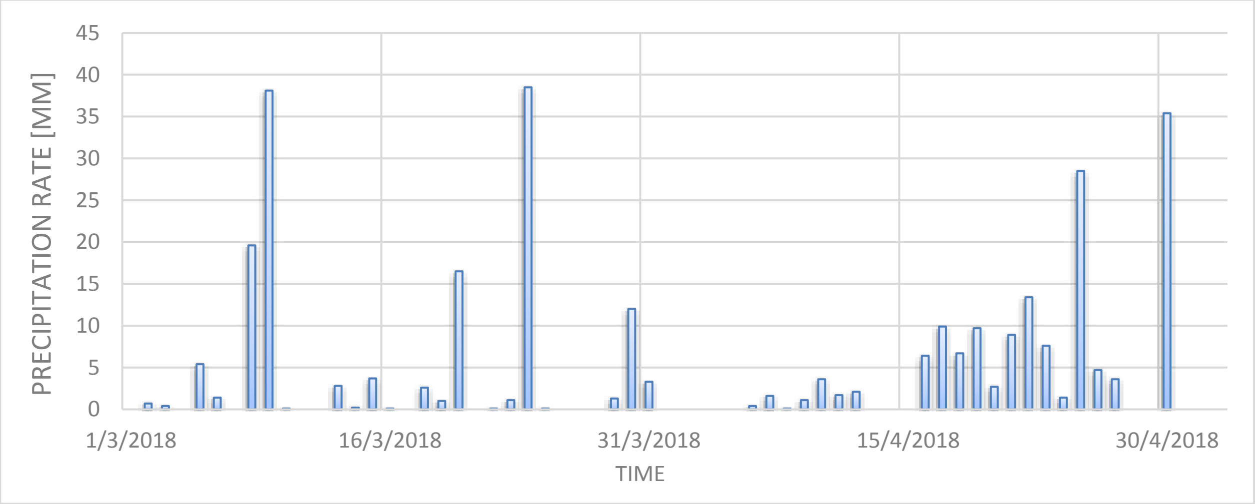

Figure 2 Precipitation during field experiment (mm/day)

The water surplus during the field experiment amounted approximately 90 mm and can be calculated by subtracting the evaporation rate from the precipitation rate over a given timeframe. An average daily evaporation of 3.5 mm day^{-1} can be assumed according to Sevenhuysen & Maebe (1995), the approximated evaporation amounted 210 mm during these 60 days. Unfortunately, no full year of tertiary drainage channel- and soil moisture data is available for comparison with the nutrient balance method. Given the fact that this study was carried out during Costa Rica's dry season (January through April), interpolation of the data is not possible. That is why the nutrient balance is based on a 60-day timeframe (Table 1).

The amount of potassium added to the system by fertilization (F) in San Pablo is 550 kg K_2O ha^{-1} yr^{-1} (control treatment), this equals to 457 kg of potassium yearly and to 75 kg of potassium per 60 days. Parker (1983) states that 1.35 gram of potassium per hectare is added to the system per millimetre of precipitation (P) in the Atlantic Zone of Costa Rica. With a measured rainfall amount of approximately 300 mm, the amount of added potassium reaches 0.4 kg ha^{-1}. Potassium is removed from the system by product harvest (H), by fruit removal in this case. The total amount of potassium removed by product harvest depends on two factors, the total yield and the nutrient concentration in the fruit. The yield amounted to over 48 tonnes per hectare in 2015 (CORBANA, 2016). The nutrient concentrations in the dry matter of bananas is according to Costa Rican data 2.07 % for Potassium respectively (Stoorvogel et al., 2013). The dry matter content of bananas amounts 20.4%. The plantation has throughout the year a continuous production, therefore the total amount of potassium removed from the system by product harvest is valued at 34 kilograms per hectare per 60 days. Based on the nutrient balance, a total loss of 41 kg potassium per hectare is expected over the stated timeframe, this is 54% of the total amount potassium added to the system by fertilization and precipitation. Assuming a water surplus of approximately 90 mm over the given timeframe, this results in an expected potassium concentration of 46 mg/L. The potassium balance method does not allow to distinguish between losses caused by surface runoff or leaching.

4.1.1 Fertilizer experiment

Table 1 shows the consequences of extra potassium addition to the system on the potassium balance. Based on the balance a total loss of 55 and 69 kilogram potassium per hectare is expected over the stated timeframe of 60 days, for treatment 1 and treatment 2 respectively. This is equivalent to 62- and 68% of the total amount potassium added to the system during this period. Reasoning from the water surplus of 90 mm, this results in expected potassium concentrations of 62- and 76 milligrams per litre. Assuming a negligible effect of extra potassium on the total yield and the nutrient concentration in the fruit, leads to the fact that all extra added nutrients run to waste.

Table 1 The potassium balance per treatment during the study timeframe of 60 days and the actual water surplus of 90 mm.

Description	**Unit**	**Control treatment**	**Treatment 1**	**Treatment 2**
F	kg ha^{-1}	75	89	102
P	kg ha^{-1}	0.4	0.4	0.4
H	kg ha^{-1}	34	34	34
Q + L	kg ha^{-1}	41	55	69
Monthly water surplus	mm	90	90	90
Expected concentrations	mg/L	46	62	76

4.2 Actual potassium loss

4.2.1 Tertiary drainage channels

The actual potassium concentration found in tertiary drainage channels of the control treatment plots amounted on average 1.3 mg/L (±1.05 S.D.). This concentration equals to an actual potassium loss of 1.2 kg ha^{-1} over the given timeframe, in combination with the actual water surplus of 90 mm (60 days), only 1.5% with respect to the total amount of potassium added to the system. The potassium concentrations in the tertiary drainage channels of both the eastern (0.65 mg/L) and western control treatment plot (2.46 mg/L), were significantly lower ($p < 0.05$) than the expected potassium concentration (47 mg/L) based on the monthly nutrient balance.

In the plots of treatment 1 and treatment 2 amounted the average potassium concentration in the tertiary drainage channels 2.3 mg/L (±2.8 S.D.) and 2.9 mg/L (±5.3 S.D.). Values of both the eastern and the western plots were combined to obtain these averages. Both the potassium concentration of the tertiary channels located in the plots of treatment 1 (2.3 mg/L) and treatment 2 (2.9 mg/L) are significantly higher ($p < 0.05$) than the average potassium concentration in the channels of the control treatment (1.3 mg/L). The concentration measured in the channels of treatment 2 are not significantly higher than the concentration measured in the channels of treatment 1 ($p = 0.21$). These average tertiary channel concentrations (2.3 mg/L and 2.9 mg/L) in combination with the actual water surplus of 90 mm, results in actual potassium losses of 2.1 kg ha^{-1} (treatment 1) and 2.6 kg ha^{-1} (treatment 2) during the study timeframe (Table 2). These actual losses equal to 2.3- and 2.6% of the total amount of potassium added to the system.

Table 2 Mean potassium concentrations in the tertiary drainage channels and actual nutrient losses per treatment during the study timeframe of 60 days and the actual water surplus of 90 mm.

Description	**Unit**	**Control treatment**	**Treatment 1**	**Treatment 2**
Mean K in drainage channel	mg/L	1.3	2.3	2.9
Actual nutrient loss	kg ha^{-1}	1.2	2.1	2.6

Striking is the difference between the east and west side of the plantation, where in the east side of the plantation application of extra potassium leads to an increased concentration in the drainage system. Leads on the west side of the plantation application of extra potassium to the opposite effect (Figure 3). Because of this contradiction, there is no overall significant effect caused by the different fertilization treatments on potassium concentrations in tertiary channels. Since, the concentration measured in the channels of treatment 2 were not significantly higher than the concentration measured in the channels of treatment 1 ($p = 0.21$). However, averages show that in the plots where more potassium fertilization was applied, higher potassium concentrations were also found in the tertiary drainage channels. A strong relative potassium concentration can be observed, an increase of 76% between the control treatment and treatment 1 and an increase of 26% between treatment 1 and treatment 2.

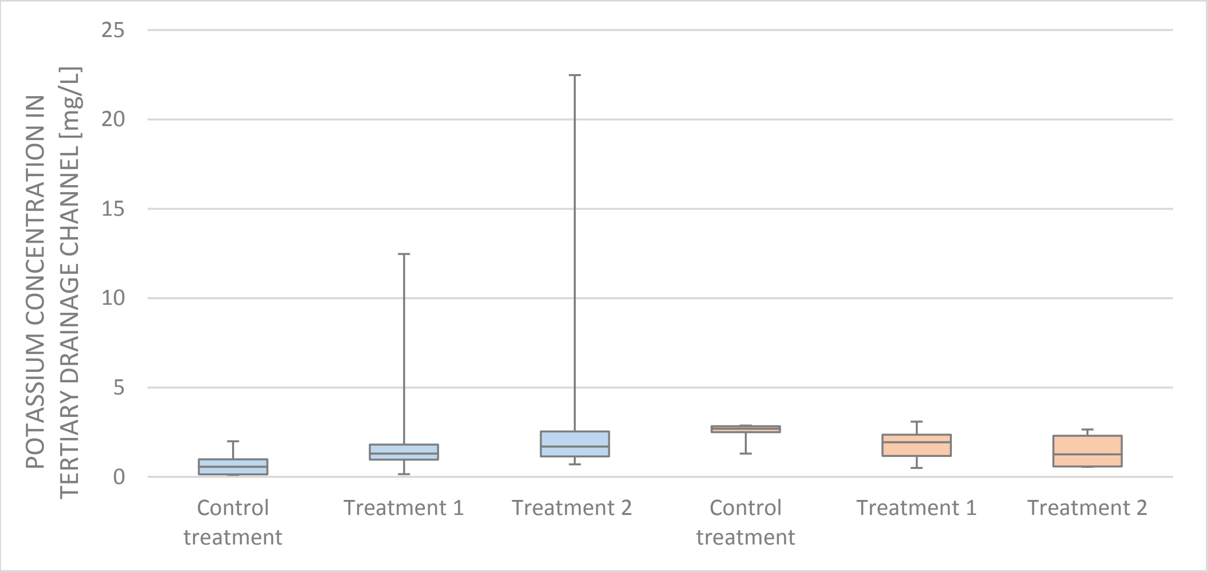

Figure 3 Potassium concentrations in tertiary drainage channels with different fertilization quantities in the eastern (blue) and western (orange) plots of the plantation.

Extreme outliers are visible at the plots in the west (Figure 3). On April 17, potassium concentrations of 12.2 mg/L (treatment 1) and 22.2 mg/L (treatment 2) have been observed.

4.2.2 Soil moisture

The average potassium concentrations found in the soil moisture of the control treatment plots, at a depth of 120 centimetre, amounted at the band position 0.7 mg/L and 0.5 mg/L at the inter row position. These concentrations in combination with the actual water surplus during the given timeframe, result in an actual loss of potassium of 0.6 and 0.5 kg ha^{-1} at the band- and inter row position respectively. These potassium losses equal to losses through leaching of 0.8 % (band) and 0.6 % (inter row) of the total applied potassium. The potassium concentration in leaching water is rather low. Potassium concentrations by surface runoff losses (1.3 mg/L) are more than 2 times higher than the potassium concentrations by leaching losses.

The average potassium concentrations found in the soil moisture of the different treatments (eastern plots only), at a depth of 120 centimetre, are shown in Table 3. Concerning the measurements in the band position of the plots, no significant increase of the potassium concentration in soil moisture has been observed in relation to increased potassium application. On the contrary, the mean average potassium concentration observed in the plot of treatment 1 (0.4 mg/L) is significantly smaller ($p < 0.05$) than the observed mean concentration in the control treatment plot (0.7 mg/L). The observed mean concentration in the plot of treatment 2 (0.8 mg/L) is neither significantly larger ($p = 0.093$) than the concentration observed in the control treatments plot. Concerning the measurements in the inter row position of the plots, the potassium concentration in the soil moisture of treatment 1 is significantly larger than the concentration in the control treatment plot ($p < 0.05$). Meanwhile, the concentration measured in the treatment 2 plot is significantly smaller than both the measured potassium concentration in the treatment 1 plot ($p = 0.000$) and the control treatment plot ($p = 0.000$). Odd is the fact that at the inter row position of the eastern plot of treatment 1, a much higher average concentration is found (2.4 mg/L) than at the band position (0.4 mg/L).

Table 3 Average potassium concentrations in soil moisture at a depth of 120 cm in the eastern plots, at both the band and inter row position with corresponding nutrient losses, based on the actual water surplus of 90 mm.

Description	**Unit**	**Control treatment**		**Treatment 1**		**Treatment 2**	
		Band	Inter row	Band	Inter row	Band	Inter row
Mean K in soil moisture	mg/L	0.7	0.5	0.4	2.4	0.8	0.2
Nutrient loss	kg ha^{-1}	0.6	0.5	0.4	2.2	0.7	0.2

The average potassium concentration in soil moisture samples in combination with the actual water surplus during the given timeframe (90 mm), results in an actual loss of potassium varying between 0.4 and 0.7 kilogram per hectare at the band position and between 0.2 and 2.2 kilogram per hectare at the inter row position. The relative losses are very small and are lower than 1% of the total applied potassium during the given timeframe. An exception is the relative loss of potassium at the inter row position of the eastern plot of treatment 1 (2.36%).

5. Discussion

5.1 Potassium in tertiary drainage channel

The average potassium concentration found in the tertiary channels of the control treatment in this study amounted to 1.3 mg/L (±1.05 S.D.). A big difference between the eastern (0.65 mg/L, n=27) and the western plot (2.46 mg/L, n=15) has been observed. This difference is most likely caused by fertilization practices (application on different days), or differences in infiltration capacity of the soil. Despite the fact that both soils are a class 2 soil (Jaramillo & Vásquez, 1990), there is sufficient variation in characteristics within a soil class to cause these differences. Yet, the found concentrations are in line with the concentrations found by De Bie (2017) in the same banana plantation ("San Pablo"), which amounted to an average potassium concentration in the tertiary channels of 1.2 mg/L. A similar study carried out in a banana plantation in Siquires (González, 1989), approximately 20 kilometres away from the research location, revealed similar results. In Siquires, the mean concentration of potassium amounted 1.3 mg/L in the drainage system. On a banana plantation located at the experimental station of 'Los Diamantes' in Guapiles (about 50 km away from San Pablo) potassium concentrations varying between 3.8 and 4.6 mg/L were found in the drainage channels (Rosales et al., 1992). This difference can be explained by the various soil types. Probably, the capacity of clay minerals to fix potassium is less in the soil in the plantation located in Guápiles. Besides, Rosales et al (1992) took measurements during the wet period in Costa Rica (from August till November), this also affects nutrient losses.

5.2 Potassium in soil moisture

The potassium concentrations found in the soil moisture at a depth of 120 centimetre were on average 0.73- (band) and 0.64 mg/L (inter row). These concentrations were very similar to the results found by De Bie (2017), as can be seen in Table 4. De Bie (2017), which also took samples at 60 cm depth, states that increasing depth causes a decreasing nutrient concentration in the soil moisture. The nutrient loss over depth is a consequence of the nutrient uptake in the root zone. This effect is strong in the band, where over 80 percent of the potassium is taken up by the plants. The effect is so strong that the nutrient concentrations at 120 cm depth in the inter row and band position are nearly the same. As a consequence, nutrient concentrations in the leaching water are low.

Table 4 Average potassium concentrations from lysimeters from different positions, depths and studies.

	Band - K [mg/L]		**Inter row -** K [mg/L]	
Depth [cm]	De Bie (2017)	Current research	De Bie (2017)	Current research
60	4.3 (1.9)	NA	0.8 (0.2)	NA
120	0.8 (0.4)	0.73 (1.06)	0.5 (0.5)	0.64 (0.56)

De la Cruz et al. (2001) did a field experiment in order to study the effect of weed on the amount of nutrients in the soil and the soil solution in Guácimo (about 40 km away from San Pablo). The average concentration of potassium on 90 cm depth was 5.5 mg/L. Despite of the nutrient concentration decrease over depth, the cause of the differences in potassium concentrations must lie elsewhere. Since, the measured concentration in the soil moisture at 60 cm measured by De Bie (2017) lies lower than the concentration measured at 90 cm depth by De La Cruz (2001). This can have various causes, either hydrological, plant physiological, pedospherical or by differences in management practices, combinations are also plausible. Probably are the differences caused by a different soil type, and then in particular its infiltration capacity and cation exchange capacity (CEC). The plantation in Guácimo is located on an alluvial fan with a sandy soil (CEC = 1-5 meq/100g) and a gravelly/ sandy subsoil, characterized by a high infiltration capacity and hydraulic conductivity (Rosales et al., 1992). The soil of San Pablo is an alluvial soil, the texture of the soil in the plantation is clay loam (CORBANA, 2012). Clay loam has a typical CEC varying between 15 and 30 meq/100g. Soils with a high CEC are less susceptible to leaching of cations such as potassium (CUCE 2007).

5.3 The potassium balance

The nutrient concentrations calculated by the nutrient balance (formula 2) are extremely overrated in comparison with actual measured nutrient concentrations in both the tertiary channel water and the soil moisture. The estimated channel values in comparison with the average measured values differ by a factor 36, 27 and 27, for the control treatment, treatment 1 and treatment 2 respectively. In soil moisture they differ even more. This is not in accordance with the differences found by De Bie (2017), where calculations differed by a factor 8 to the actual measured nutrient concentrations. This difference is caused by differences of the input parameters of the potassium balance, and moreover in the water surplus which is used to convert total nutrient loss in kg ha^{-1} (Q+L) to expected potassium concentrations in soil moisture and drainage channels in mg/L. De Bie (2017) based her input parameters on a database with 10 years of data (2005-2015) covering the amount of harvested fruit, applied fertilizers and precipitation data from the San Pablo plantation. She also used this data for calculating the water surplus, 1950 mm annually. This is 320 mm converted to the timeframe of 60 days. The actual measured water surplus amounted 90 mm over the study timeframe, the field campaign was held during Costa Rica's dry season. The nutrient balance assumes that all available nutrients enter the water surplus, a likely assumption given the mobility of potassium . With a little water surplus, this results in extreme calculated concentrations. In reality, little water surplus means little risk of leaching and surface runoff, given that the infiltration capacity of the soils in the Atlantic zone of Costa Rica often exceed these rather low rainfall intensities. That small water surpluses not cause surface runoff and leaching, is the reason for the extreme overestimation of expected potassium concentrations in drainage channels and soil moisture. The measured outliers of the 17th of April, with promoting conditions for surface runoff, therefore differ only a factor 5 (treatment 1) and a factor 3.5 (treatment 2) from the calculated values. Extreme runoff events are way better approached by the potassium balance than the base flow.

5.4 Nutrient distribution in the system

The potassium balance can be used to gain insight in the distribution and behaviour of the nutrient in the system. The known terms of the potassium balance are; potassium addition by fertilization (F) and by precipitation (P) and potassium loss by harvest (H). The amount of potassium added to the system by fertilization is accurately known. Also, strongly fluctuating precipitation has only limited effect on the potassium balance (1.35 g potassium per mm) and can the term can in fact be neglected. Potassium loss by harvest can be estimated properly, when both the numbers on yield and the potassium concentration in the fruit are reliable. This implies that the answer on the question where the potassium goes, lies in either the surface runoff (Q) and/or the leaching (L) term.

Figure 4 is composed of the soil moisture data obtained by De Bie (2017) at 60 cm depth and the soil moisture data obtained at 120 cm depth during the current study. The tertiary channel concentration obtained during the current study has also been implemented. Figure 4 is based on the control treatment. The concentration of potassium in the tertiary channel ([K] =1.3 mg/L) can under no circumstances only be supplied by groundwater flow ([K] < 0.73 mg/L). This means that at least partially the tertiary channels are fed by superficial subsurface flow or surface runoff.

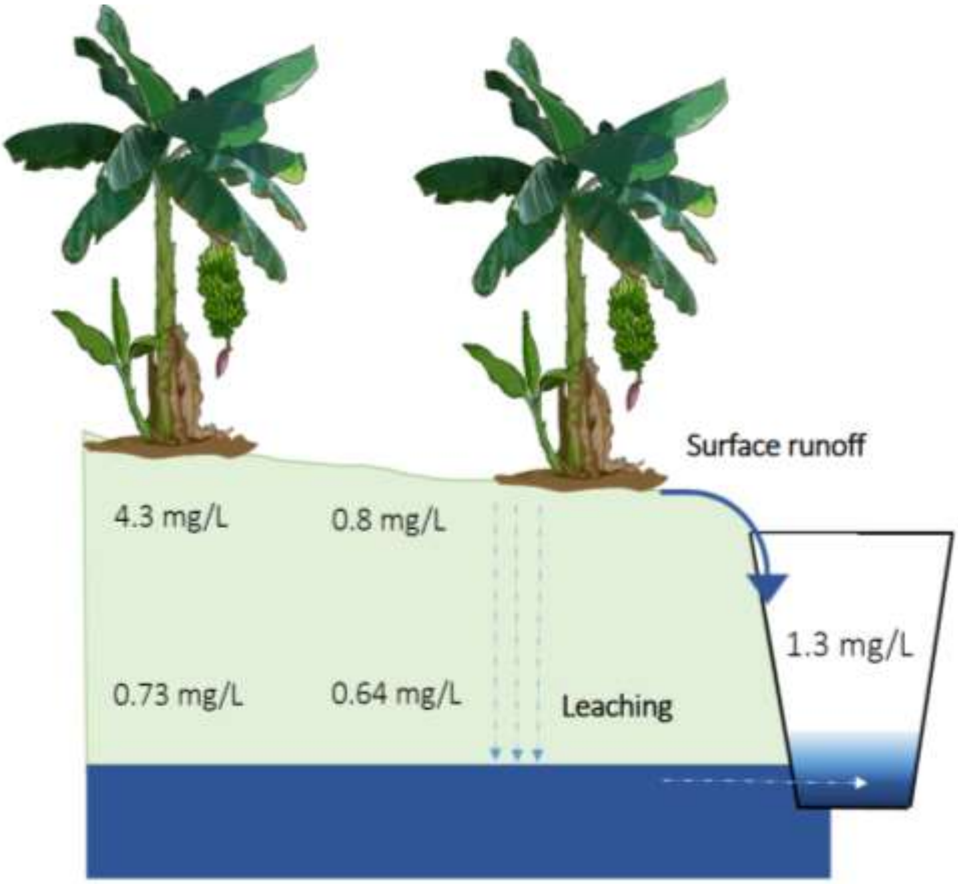

Figure 4 Illustration of the nutrient distribution in the tertiary drainage channel and the soil water under the fertilizer band and in the inter row, both at 60 and 120 cm depth. Based on the potassium application of the control treatment.

Besides, Figure 4 rules out the possibility that a major part of the applied potassium is lost through deeper leaching, because the potassium concentration in soil moisture at 120 centimetre depth amounts on average 0.73 mg/L (band), and at the inter row position even less (0.64 mg/L). This means that the main potassium losses are caused by surface runoff (Q). The base flow dominates most of the time, resulting in potassium concentrations of 1.3, 2.3 and 2.9 mg/L on average, in the channels of the control treatment, treatment 1 and treatment 2. However, the extreme outliers measured at the plots in the west, emphasize the expected potassium losses by surface runoff. On April 17th , potassium concentrations of 12.2 mg/L (treatment 1) and 22.2 mg/L (treatment 2) have been observed.

Serious potassium losses from the system are caused when these concentrations are accompanied by large quantities of water. These surface runoff events drain many times greater amounts of water than the dominating base flow does. On April 17th a fair amount of precipitation fell, in total 6.6 mm in the 7 hours prior to the measurements. De Bie (2017) showed that potassium concentrations in the drainage channels during peak flow (1.5 mg/L) are almost four times bigger than the concentrations during periods without rain (0.4 mg/L). Besides, the fertilizer application that specific day (April 17th), probably strongly affected the elevated potassium concentrations in the channels. This reveals the importance of timing the fertilizer application. Applying fertilizers just before or during rain showers, results in immediate large losses of the agrochemicals. This applies in particular to highly mobile fertilizers (such as potassium). As De Bie (2017) rightly remarked, have the findings related to the major potassium losses due to surface runoff, consequences for the tenability of the dome construction. The dome construction promotes superficial drainage. Despite its positive effect on drainage, has the dome construction a reinforcing effect on potassium losses, as well as other agrochemicals. Whether the benefits of the dome construction (lower groundwater levels result in higher yields (Avilán et al., 1979)) outweigh the costs (reinforcement of agrochemical losses) should be investigated.

As mentioned in the theoretical background (chapter 2) is the rainfall distribution strongly affected by the canopy of the banana plant, causing a 20- to 28- fold higher water load at the plant base.. The water surpluses caused by stem flow in combination with the fertilization practices at the plant base, most likely result in high nutrient losses. Despite the high expected nutrient losses caused by surface runoff, justifies Figure 4 the position of the fertilizer application. Most of the plant roots are located around the plant base, and nutrient uptake in this zone is many times higher than in inter row positions. Possible alternatives of fertilizer application are favorable, such as incorporating the fertilizers in the soil. Drought in banana plantations can affect the potassium stock in two ways, as can be seen in Figure 5.

Drought either inhibits water uptake and the associated nutrient intake, thus the K stock in the soil builds (Scenario 1). Banana plants are susceptible to water stress (Blom-zandstra, 2017). This is self-reinforcing, poor potassium uptake will result in less water circulation in the plant. This will make the plant more susceptible to drought and temperature changes. Mahouachi (2007) found reduced levels of K^+ in banana plants under drought conditions, Mahouachi used powdered fruit tissue in order to determine macronutrient composition in the plant tissue.

Similar results were found by Restrepo-Diaz et al., 2008) in the leaves of water-stressed olive plants and Ge et al. (2012) found a sharp decreases in total K uptake op maize (*Zea mays* L.), caused by drought stress. An opposite effect on the K stock in the soil is also possible, when more light means more growth (no water stress), resulting in a decrease of the K stock in the soil (Scenario 2).

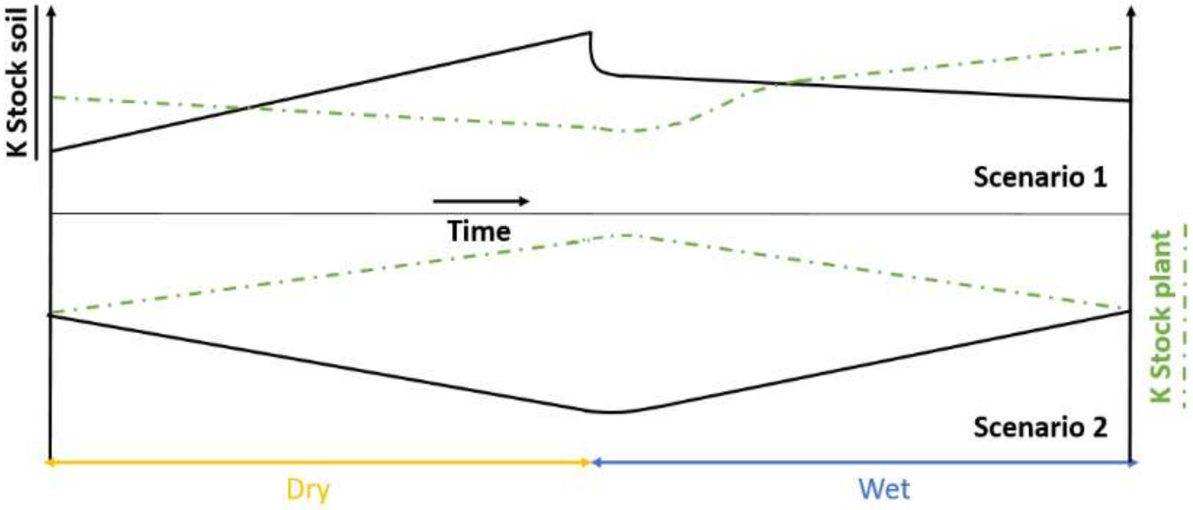

Figure 5 A two scenario theoretical frame work in order to understand the potential effects of drought on both the potassium stock in the soil and the banana plant.

5.5 Agrochemicals

Potassium is an excellent proxy to map the water flows in the system, given the high mobility of the nutrient. Besides, its extreme mobility makes it possible to draw conclusions on other agrochemicals based on potassium behaviour in the system. The fact is, no agrochemical will leach faster, or to a greater extent than potassium. Potassium behaviour can therefore be used as a worst case scenario situation for any given agrochemical. The different agrochemicals for fertilization and pest control used in banana production, with accompanying activity/ application methods can be found in Bellamy (2013). It concerns several synthetic and organic fertilizers (especially nitrogen and phosphorous), and various pesticides, nematicides, herbicides and fungicides. Potassium fertilizer is in particular very sensitive for surface runoff due to the application method (band application). Some agrochemicals are aerially applied (e.g. fungicides), others in a similar way to artificial fertilizer (e.g. nematicides) or only indirectly at the soil (e.g. herbicides) (Bellamy, 2013). Also, many of these agrochemicals are highly resistant to natural degradation processes and tend to accumulate in the soil, in contrast to potassium (Bollag et al., 1992). Agrochemicals directly interact with soil through the processes of adsorption and covalent bond formation (Khan, 1978), or are transformed by biotic or abiotic processes. Ideally, the agrochemicals are mineralized to release carbon dioxide, water, and mineral elements. However, varying intermediate products may also form and are often toxic. Agrochemicals and their metabolites can be transported through the soil by the processes of leaching, bioconcentration and volatilization. This in contrast to potassium, which mainly is transported by water.

6. Conclusion and Recommendations

This study gave insight in the distribution and behaviour of potassium in the banana production system and showed that the main potassium losses in San Pablo are caused by surface runoff (Q). The base flow dominates most of the time, resulting in potassium concentrations of 1.3, 2.3 and 2.9 mg/L on average, in the channels of the control treatment, treatment 1 and treatment 2. The study rules out the possibility that a major part of the applied potassium is lost through deeper leaching (L), since the potassium concentrations in soil moisture of the control treatment plots at 120 centimetre depth on average 0.7 mg/L (band), and at the inter row position even less (0.5 mg/L) amounted. The extreme outliers measured in the tertiary channels, emphasize the expected potassium losses by surface runoff. On April 17th, potassium concentrations of 12.2 mg/L (treatment 1) and 22.2 mg/L (treatment 2) have been observed. In reality, the biggest losses are suffered either during intense precipitation and/or right after fertilizer application. Only the outliers exceed the maximum allowable potassium concentration of drinking water, 12 mg/L (WHO, 2009). The potassium balance gave also insight in the distribution and behaviour of the nutrient in the banana production system. The nutrient concentrations calculated by the nutrient balance (formula 2) are extremely overrated in comparison with the found nutrient concentrations in both the tertiary channel water and the soil moisture. Little water surplus means little risk of leaching and surface runoff, given that the infiltration capacity of the soils in the Atlantic zone of Costa Rica often exceed these rather low rainfall intensities. That small water surpluses not cause surface runoff and leaching, is the reason for the extreme overestimation of expected potassium concentrations in drainage channels and soil moisture.

The findings related to the major potassium losses due to surface runoff have consequences for the tenability of the dome construction. The dome construction promotes superficial drainage. Despite its positive effect on drainage, the dome construction has a reinforcing effect on potassium losses. Whether the benefits of the dome construction (lower groundwater levels result in higher yields) outweigh the costs (reinforcement of agrochemical losses) should be investigated.

All agrochemicals behave differently in the system. Potassium on the one hand is mostly conveyed through water. Others can accumulate in the soil (by adsorption and covalent bond formation), be transformed by biotic or abiotic processes and bio-concentration or volatilization can occur. These processes are complex and vary with season, climate, soil type and farming practices. If no point source pollution takes place, no serious water quality problems are expected in ecosystems downstream of, or adjacent to the banana production zone in Costa Rica.

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