ZIBELINE INTERNATIONAL PUBLISHING

Journal Clean WAS (JCleanWAS)

DOI: http://doi.org/10.26480/jcleanwas.02.2020.84.88

ISSN: 2521-0912 (Print)
ISSN: 2521-0513 (Online)
CODEN: JCOLBF

CrossMark

RESEARCH ARTICLE

REVIEW ON THE ROLE OF EARTHWORMS ON HILLSLOPE HYDROLOGY AND SOIL EROSION WITH SPECIAL REFERENCE TO DANUM VALLEY, SABAH, MALAYSIA

Noor Ain Yahya, Carolyn Payus, Kawi Bidin*

Faculty of Science and Natural Resources, Universiti Malaysia Sabah, Jalan UMS, 84000, Kota Kinabalu, Sabah, Malaysia.
****Correspondence Author Email: kbidin@ums.edu.my***

ARTICLE DETAILS

Article History:

Received 03 October 2020
Accepted 05 November 2020
Available online 07 December 2020

ABSTRACT

Hydrological routes exist through active burrowing of soil fauna, and in numbers improve soil drainage systems. Earthworms are of particular interest because their presence is known widely to increase infiltration and reduce erosion rates by creating macropores and stable casts. Ideally during non-extreme rainfall events on flatlands, earthworm macropores lengthens the time prior to soil surface saturation thus slowing down occasions of overland flow resulting in runoff. Hypothesizing similar effects on hillslopes with gradients can be misleading whereas laboratory experiments which try to recreate and simulate field consistency cannot match the natural soil architecture which is vital in the dissection of the many bio-geophysical processes involved in the rainfall-runoff process. This review paper aims to summarize past studies conducted around the world and highlighting possible gaps on earthworm's studies related to hillslopes and erosion.

KEYWORDS

Review, earthworm, hillslope, erosion.

1. Introduction

Soil erosion negatively affects public health and the environment (Pimentel, 2006). It reduces water quality and soil productivity, cause siltation of reservoirs and reduces plant, animal plus microbe biodiversity (Panagos et al., 2018; Jouquet et al., 2012; Pimentel, 2006). Productivity is also low on eroded soil because it is difficult to establish seedlings during nutrient and organic matter shortage (Johnson et al., 2012). Eroded from its original state by wind and water, its detachment is aggravated by raindrops and flowing water which is then transported downslope (Omar et al., 2018). A group researcher outlined some of the importance of soil security (Steffan et al., 2017). In a food supply chain, a healthy soil guarantees crops with nutrients thus, benefiting the humans consuming it. It is also home to soil fungi and bacteria that compete to inadvertently suppress dangerous fungus such as *Coccidioides* spp., ensuring endemism of the serious disease; Valley Fever or Coccidiodomycosis. The future of discovering new antibiotics also depends on isolating them from soil organisms. Earthworms can contribute to improving soil health and quality because their burrows, ingesting of soil or cast production can activate dormant or improve microbial biomass and bacterial diversity (Lavelle et al., 2007; Chhotorray et al., 2011 and van Schaik et al., 2014). Their activity encourages water preferential flow paths that can reduce surface runoff and increase infiltration (Shipitalo and Le Bayon, 2004).

Earthworms directly influence many of the runoff and erosion processes (Bertrand et al., 2015; Jouquet et al., 2012). Their presence is a positive indicator for agriculture and activity correlates to the improvement of soil conditions (Coleman and Wall, 2015; Peres et al., 2010). However, Danum Valley is different than the rest of the world as a pristine tropical forest still rich in biodiversity that has forests in different stages of regeneration (Reynolds et al., 2011). Past researchers in there have not tackled the full importance or strength of earthworm presence on hydrological properties but have hinted on their roles (Bidin et al., 1992). Their contributions to any of the improvements also have not yet been proven applicable in tropical conditions of Danum Valley. There is a question on whether these betterments are species dependent, distribution related or abundance reliant? Does plant cover and above ground vegetation make it easier for worms to thrive and improve soil conditions or do climatic condition (seasonality), slope gradients and soil compaction actually hinder their activity? Do their activity of producing casts actually contribute more material to be eroded as runoff sediment?

2. Literature Review

Hydrological studies conducted in tropical hillslopes of Puerto Rico noted the implications of earthworm removal from bounded plots (Larsen et al., 2014). Compared to controls there is a doubling of runoff, while the erosion of soil and organic matter increased by a factor of 4.4. Transport of fine litter increased by factor of 3.4 and was up to 5.4 for mineral soil erosion. They concluded two attributing factors at microtopographic scale; (1) reduction in soil porosity due to less burrowing and reworking of the soil and (2) reduced casting activities by earthworms that decreases

Quick Response Code	Access this article online	
	Website: www.jcleanwas.com	**DOI:** 10.26480/jcleanwas.02.2020.84.88

Cite the Article: Noor Ain Yahya, Carolyn Payus, Kawi Bidin (2020). Review On The Role Of Earthworms On Hillslope Hydrology And Soil Erosion With Special Reference To Danum Valley, Sabah, Malaysia. *Journal Clean WAS, 4(2): 84-88.*

soil surface area and surface roughness; making soil easier to break into finer sediment which ends up washed away during the rain. They also encouraged understanding the role of macrofauna towards soil-water resources because strategies for land and ecosystem management are complex. Earthworms are one of the soil faunas in forested environments that affect macro-porosity and soil structure. Areas that have undergone intentional anthropogenic reduction of earthworm population usually resulted in a degradation processes i.e. lowered infiltration of rainfall and increased soil erosion due to more surface runoff. Similar events happen when disturbance to soil or vegetation is unintentional.

On the other hand, out of all the possible factors influencing runoff and erosion, soil compaction was found to be the key determining factor for soil loss in selective logged-over Danum Valley forest (Cleophas et al., 2017). Two decades of logging resulted in (1) skid trails (by the traversing of heavy machineries), (2) large log landing areas and (3) major soil compaction from the dragging of logs upslope (Reynolds et al., 2011; Pinard et al., 2000; Clarke and Walsh, 2006). Through the bounded plot method, they quantified runoff and sediment production for logged hillslopes, skid trails and undisturbed hillslopes. Soil loss was highest in skid trails, closely followed by logged hillslopes while undisturbed hillslopes recorded values of 20 times lower at 2.72, 2.56 and 0.13 t ha^{-1} yr^{-1} respectively. Danum Valley is rich in species diversity, therefore by not including biotic factors such as earthworms into their study scope; results from just physical properties may be inconclusive.

Past Danum Valley researchers have related earthworms to some hydrological processes (Waidi, 1991; Sayer, 2006). The former recorded total number of earthworm casts throughout the 10 x 2.2 m^2 stretch of his bounded runoff plots to find that suspended sediment concentration from runoff was greater when worm cast numbers were high. Casts may contribute to aggregate stability and result in less available - small aggregates erodible by raindrops. The latter author on the other hand briefly mentioned how faunal burrow activity contributes to soil piping. An indirect connection could be derived from studies that quantified and studied earthworm casts (Johnson et al., 2012). They observed that casts were more difficult to crush compared to its surrounding soil and hardened because soil with infused with organic glue. If removed (as Danum Valley experienced some high intensity storms and much rainfall), they found that earthworms take less than 5 days to create new ones and the rate of production is higher in primary and secondary forests than degraded forests during the wet season.

Table 1: Summary of aspects studied around the world and the main conclusion of their work.

Location	Aspect of study	Target/ collected earthworm species	Findings	Source
Vietnam	A rainfall simulation experiment to observe influence of earthworms on runoff and erosion on steep slope (~ 37%) fallow	1.*Amynthas khami*	1. Globular and large earthworm casts significantly improves infiltration and decrease soil loss	Jouquet *et al.,* 2012
		2. *Pheretima leucocirca*		
		3. *Pheritima californica*	2. Earthworm casts have greater impact on ecosystem functioning than abundance/ biomass/ diversity	
		4. *Dichogaster modigliani*		
		5. *Pheretima spp.*	3. Simulation cannot describe overall hillslope dynamics	
Puerto Rico	Observe effects of earthworm on slopewash, surface runoff and fine litter transport on tropical forested hillslope	1. *Pontoscolex corethurus*	1. Disturbance to area causes reduction to earthworm population thus sparking a chain of events namely increase of runoff, erosion, fine litter downward transport and reduction on rainfall infiltration	Larsen *et al.* , 2014
		2. *Amynthas rodericensis*		
		3. *Estherella gates*		
Germany	Studying the link through rainfall simulation, between spatial distribution of earthworm ecological groups to macropore number and infiltration pattern on different agricultural landforms (hilltop, valley, slope)	1. *Octolasium cyaneum*	1. Number of macropores created depend on abundance and biomass of earthworms (especially anecics), which strongly affects infiltration patterns	van Schaik *et al.* , 2014
		2. *Aporrectodea caliginosa*		
		3. *Aporrecyodea rosea*		
		4. *Lumbricus terrestris*	2. Deep infiltration is rapid when macropores are larger and connected to soil surface if less than 30cm soil depth	
		5. *Lumbricus rubellus*	3. If worm burrows are connected to larger tunnel, water will also rapidly flow through the lateral hole	
		6. *Lumbricus castaneus*	4. Infiltration via macropores, not macropore-soil matrix	
Colombia	Focus on anecic and endogeic casts effects on soil carbon cycle (/soil organic matter) in the	1. *Martiodrilus sp.*	1. There is a physical stabilation of plant debris upon ingestion of litter by earthworms	Guggenberger *et al.,* 1996
			2. Casts structural stability due to earthworms	
Brazil	Experiment on worm aggregation on upper 10-20cm	General	1. Earthworms improve hydraulic properties of soil (below surface) via their biogenic aggregation	in Lavelle *et al.* 2007
Europe	Studying effects of erosion on soil biota and quantifying their effects on erosion	General	1. Requirement of factoring earthworms into soil erosion models for reliable estimates	Orgiazzi and Panagos, 2018
			2. Soil erosion displaces many earthworm individuals but earthworm presence can reduce this process by 50%	
A review of the tropics and semi arid subtropical area	1. Quantifying mechanism of earthworm influence on erosion	1. *Aporrectodea tuberculata*	1. Endogeics control soil erosion by modifying soil structures and its physical properties	Blanchart *et al*., 2004
		2. *Pontoscolex corethurus*		
	2. Analyzing how much functional groups (compacting and decompacting species) by aggregation, aggregate stablity, total porosity and pore size distribution influence soil erodibility	3. *Millsonia anomala*	2. Soil loss occurs more due to decompacting species that create small casts prone to surface sealing. However, they can delay runoff due to the increased soil porosity and infiltration. It is opposite for compacting species which create stable macroaggregates insensitive to runoff or rain splash. Unfortunately soil infiltration is less effective due to the increase of bulk density	
		4. *Lumbricus rubellus&terrestris*		
		5. *Heteroporodrilus mediterreus*		
		6. *Martiodrillus sp.*		
		7. *Stuhlmannia porifera*		
		8. *Chuniodrillus zielae*		
		9. *Polypheretima elongata*		

3. Result and Discussion

3.1 Notable differences between tropical Danum Valley and other parts of the world Plant litter and above ground vegetation

Notable differences can be observed between role of earthworms in tropical Danum Valley and other parts of the world. The first perspective is the relationship between earthworms with plant litter and above ground vegetation. Many studies found plant litter to influence soil erosion rates because of their strong link to earthworms (Dechaine et al., 2005; Blanchart et al., 2004; Lavelle et al., 1999). Plant litter is consumed by anecic earthworms, facilitating its fragmentation and incorporation into soil, thus helping vegetation growth (Laossi et al., 2010). Some researchers found that if plant litter was high in primary resources, earthworm casts are bound to be more structurally stable due microbial metabolism in its gut (Guggenberger et al., 1996). Mechanically, the energy by raindrops causes sheet erosion by dislodging soil particles (i.e. our concern is the casts created by earthworms) and this is less likely to occur when there is a combination of cover by plant biomass regardless whether living or dead (Pimentel, 2006). Waidi mentioned that due to the thick and continuous amount of litter cover in Danum Valley, resulting surface runoff and sediment (note: including by casts) is in lower quantities (Waidi, 1991). Effect of vegetation there was also focused because plants affect runoff by preventing soil and litter from being swept away by wind and water, aside from reducing the erosive power of raindrops through canopy interception (Cleophas et al., 2017). However, some researcher concluded that it is the combined role of plant material and invertebrates which influenced soil erosion and surface water movement (Waidi et al., 1992). Role of earthworms can be further studied here.

3.2 Earthworm distribution

The second factor is the earthworm's distribution effects on hillslope hydrology. The different levels of disturbance (i.e. undisturbed, moderately impacted and highly disturbed forest fragments) in Sabah could reflect the number of earthworms collected from sampling efforts because they are disturbance-sensitive (Rao, 2013). In other parts of the world, studies found that densities could also be impacted negatively by human induced land use changes with the reduction in litter food source and protective vegetation cover (Jouquet et al., 2012). Due to a wide range of surrounding vegetation within Danum Valley with different levels of disturbance and/or lack thereof, the quality of soil organic matter from litter input should be better, increasing expectations of higher earthworm distribution. Edwards and Bohlen correlated higher earthworm abundance to higher litter quality (Edwards and Bohlen, 1996). But if the competition factor is also considered, epigiec earthworms that also feed on the same food resource as anecics affects distribution patterns and will result in varying soil water dynamics (Palm et al., 2013). Rao highlighted the need to determine whether existing earthworm abundance actually impacts soil processes and resulting ecosystem services because the knowledge of earthworms in Sabah is limited despite their proven role in other parts of the world (Rao, 2013).

3.3 Gradient and slopes

Third possible view is that if there is any correlation between gradient and slopes on earthworm activity. Pimentel highlighted the intensification of soil erosion if more than half of surface soil removed from slopes is carried downhill, ending up in waterways or valleys (Pimentel, 2006). This happens more on steep hillslopes where earthworm casts can dislodge and end up rolling downslope (Larsen et al., 1991). It is opposite on gentler slopes because earthworm casts are not main contributors to this event (Larsen et al., 2014). In a study for Danum Valley, the steepest slope (28°) did not result in the highest runoff volume or the highest sediment yield and it would be interesting to find out if earthworms played any part in this (Cleophas et al., 2017). As for they did not find the biomass abundance of earthworms impacting the steeped slope ecosystem function (Jouquet et al., 2012). However, they mentioned that tropical hillslopes are characterized by large population of soil engineers, extreme rainfall events, fast biogeochemical cycling and soil degradation. If all these factors describe Danum Valley, there could be a link between earthworm activity and its resulting impacts, if not due to its biomass abundance.

3.4 Earthworm casts

Fourth factor to consider is the amount of earthworm casts produced in Danum Valley and if it affects erosion. Biogenic aggregates created by earthworms or more commonly known as casts can reduce soil and nutrient losses besides improving infiltration. Besides that, these globular water-stable structures are better than the unstable granular termite sheetings which end up collapsing and transported during rainfall, enhancing water runoff (Jouquet et al., 2012). Freshly emitted casts are prone to removal by rain and instead contribute to soil erosion and reduction in infiltration due to surface soil seal formation. However, having these crusts does not necessarily result in runoff due to lowered hydraulic conductivity and decrease in total porosity (Jakab et al., 2013).
Dried, old earthworm casts protects soil from crusting and being detached because it increases the roughness of soil; has opposite effects on infiltration and are proven to be stable (Le Bayon and Binet, 2001; Larsen et al., 2014). Interestingly, casts can also have a gluing effect and they conveniently reduce fine litter downslope transfer when the organic materials are stuck to these casts (Larsen et al., 2014). In Danum Valley, the casts recorded as many as 1 to 31 and 2 to 130 counts per m^2 respectively (Waidi, 1991; Johnson et al., 2012). Other countries record a much higher number of casts and some are even much larger in size; having a reduced effect on runoff especially species studied in Vietnam (Jouquet et al., 2012).

3.5 Seasonality

The seasonality factor is also compared between Danum Valley and other parts of the world. A group researcher described Danum Valley to have many brief low and high intensity showers, short storm durations and the occasional multi-cell, complex plus continuous long-hour heavy rain over hundreds of square kilometres (Hazebroek et al., 2012). These single storm events could lead to soil sealing and crusting especially when clay is dominant, through continuous deposition that creates a surface clay film (Jakab et al., 2013). Some researchers also reported drought in February – early May in major ENSO years (Walsh and Newberry, 1999; Luke, 2016). In the recent study, it was reported that different plot characteristics affect rates of generated runoff (runoff depth) and that the relationship between runoff and rainfall is not direct or significant (Cleophas et al., 2017).

The effects of earthworm in a site to runoff could be looked into because when the relative dry seasons occur, earthworms are known to be less active and tend to burrow deeper (Edwards, 2004; Larsen et al., 2014). As a result, with fewer burrows could suggest less infiltration. According to Rao opportunities of sighting earthworms in Sabah are higher during rainy season due to flooding (Rao, 2013). Similar suggestions were given (Vishwakarma and Yadav, 2017). This could give an insight of possible earthworm species, their abundance and habitat preference in Danum Valley. Whether their activities intensify during the rain, whether they are the main reason that soil sealing and crusting is broken after a storm; improving soil aeration for plants and that if they also stay underground when the drought hits Danum Valley could be further investigated.

3.6 Compacted soil

Compacted soil is the last and most related factor to be reviewed for the role of earthworms on erosion and hillslope hydrology. Since soil compaction was found to be the key determining factor for soil loss in selective logged-over Danum Valley forest, therefore it would be interesting to observe if there is any difference in earthworm densities according to recovery rates and degree of compacted soil (Cleophas et al., 2017). The volume, orientation, connectivity and length of earthworm burrows can have different impacts on preferential water pathways through soil macropores (Palm et al., 2013 and van Schaik et al., 2014). However, there are limitations to the ability of earthworms to penetrate compacted soil. According to a study, the maximum pressure an endogeic earthworm can still move in is 195 kPa while for the anecics were 130 kPa (Ruiz and Or, 2018).

However, the values are outliers and the respective mean values are 92kPa and 77 kPa. They also summarize previous studies and found some species able to move through mean pressure of kPa 230 and 295 kPa. If earthworms can reduce soil compaction by creating burrows through it up to a certain level, would their migration or repopulation from neighbouring Danum Valley over decades of natural forest regeneration contribute to de-compaction and indirectly reduce soil loss? This can be supported by a statement, where they mentioned that ground level in Danum Valley experienced reduction of compaction in skid trails and log landing sites due to soil faunal activity and vegetation re-expanding compacted soil (Clarke and Walsh, 2006). If some Danum Valley areas are compacted due to these two reasons and the compactions are higher than 230 and 295 kPa, then are earthworms theoretically not present at all or are they actually not able to rework the soil into recovery? This is yet to be proven and may differ than past literature or other studies; especially due to soil type and degrees of compaction.

4. Conclusion

In conclusion, the interaction between earthworm, soil loss and the hydrological process from around the world can be the foundation to studies in Danum Valley, Sabah. Its pristine, adjacent logged-over forest and resulting compacted skid trails allows different observations to be conducted, from a quantitative point of view (i.e. abundance, number of casts, number of macropores created). Unlike other countries, this study includes a wet and dry season, diverse vegetation, and most importantly, missing data on the unexplored earthworm abundance and distribution from a local perspective. Based on this review, there are many gaps to the effects of earthworm distribution in Danum Valley and whether they have ultimately prevented or contributed to erosion.

5. References

Bertrand, M., Barot, S., Blouin, M., Whalen, J., de Oliveira, T., Roger-Estrade, J., 2015. Earthworm services for cropping systems: A review. Agronomy for Sustainable Development, 35 (2), Pp. 553-567.

Bidin, K., Douglas, I., Greer, T., 1993. Dynamic response of subsurface water levels in a zero-order tropical rainforest basin, Sabah, Malaysia. IAHS Publication, 7, 491-491.

Blanchart, E., Albrecht, A., Brown, G., Decaens, T., Duboisset, A., Lavelle, P., Mariani, L., Roose, E., 2004. Effects of tropical endogeic earthworms on soil erosion. Agriculture, Ecosystems, and Environment, 104, Pp. 305 - 315

Chhotorray, D., Mishra, C.S.K., Mohapatra, P.K., 2011. Diversity of bacteria and fungi in the gut and cast of the tropical earthworm Glyphodrilly tuberosus isolated from conventional and organic rice fields. Journal of Pharmacology and Toxicology, 6 (3), Pp. 303-311.

Clarke, M.A., Walsh, R.P.D., 2006. Long-term erosion and surface roughness change of rain-forest terrain following selective logging, Danum Valley, Sabah, Malaysia. Catena, 68, Pp. 109-123.

Cleophas, F., Musta, B., How, P.M., Bidin, K., 2017. Runoff and Soil Erosion in selectively-logged over forest, Danum Valley, Sabah. Transactions on Science and Technology, 4, Pp. 449–459.

Coleman, D.C., Wall, D.H., 2015. Soil fauna: occurence, biodiversity, and roles in ecosystem function. Soil microbiology, ecology and biochemistry, 5 (4), Pp. 111-149.

Dechaine, J.M., Ruan, H., de Leon, Y.S., Zou, X., 2005. Correlation between earthworm and plant litter decomposition in tropical wet forest of Puerto Rico. Pedobiologia, 49, Pp. 601-607.

Edwards, C.A., 2004. Earthworm ecology. CRC Press.

Edwards, C.A., Bohlen, P.J., 1996. Biology and ecology of earthworms. Chapman and Hall. Pp. 426.

Guggenberger, G., Thomas, R.J., Zech, W., 1996. Soil organic matter within earthworm cast of anecic-endogeic tropical pasture community, Colombia. Applied Soil Ecology, 3, Pp. 253-274.

Hazebroek, H.P., Adlin, T.Z., Sinun, W., 2012. Danum Valley : The rain forest. Natural History Publications : Borneo, Malaysia.

Laossi, K., Decaens, T., Jouquet, P., Barot, S., 2010. Can we predict how earthworm effects on plant growth vary with soil properties? Applied and Environmental Soil Science. Hindawi Publishing Corporation. Pp. 6.

Larsen, M.C., Liu, Z., Zou, X., 2014. Effects of earthworms on slopewash, surface runoff, and fine litter transport on a humid-tropical forested hillslope in Eastern Puerto Rico. Water Quality and Landscape Processes of Four Watersheds in Eastern Puerto Rico, Pp. 197.

Larsen, M.C., Torres-Sanchez, A.J., Concepcion, I.M., 1991. Slopewash, surface runoff and fine litter transport in forest and landslide scars in humid tropical steeplands, Luquillo Experimental Forest, Puerto Rico. Earth Surface Processes and Landforms, 24, Pp. 481-506.

Lavelle, P., Brussaard L., Hendrix, P.F., 1999. Earthworm management in tropical agroeconosystems: London. Oxford University Press, Pp. 320.

Lavelle, P., Barot, S., Blouin, M., Decaens, T., Jimenez, J.J., Jouquet, P., 2007. Earthworms as key actors in self-organized soil systems. Ecosystem Engineers - Plant and Protists, 4, Pp. 77-106.

Le Bayon, R.C., Binet, F., 2001. Earthworm surface casts affect soil erosion by runoff water and phosphorus transfer in a temperate maize crop. Pedobiologia, 45 (5), Pp. 430-442.

Luke, S.H., 2016. The effect of catchment and riparian forest quality on stream environmental conditions across a tropical rainforest and oil palm landscape in Malaysia Borneo. Ecohydrology, 10, Pp. 1827.

Jakab, G., Nemeth, T., Csepinszky, B., Madarasz, B., Szalai, Z., Kertesz, A., 2013. The influence of short term soil sealing and crusting on hydrology and erosion at Balaton uplands, Hungary. Carpathian Journal of Earth and Environmental Sciences, 8 (1), Pp. 147-156.

Johnson, S., Bose, A., Snaddon, J.L., Moss, B., 2012. The role of earthworms in nitrogen and solute retention in a tropical forest in Malaysia: a pilot study. Journal of Tropical Ecology, 28, Pp. 611-614.

Jouquet, P., Janeau, J., Pisano, A., Sy, H.T., Orange, D., Minh, L.T.N., Valentin, C., 2012. Influence of earthworms and termites on runoff and soil erosion in tropical steep slope fallow in Vietnam: a rainfall simulation experiment. Applied Soil Ecology, 61, Pp. 161-168.

Omar, M.N., Rahaman, Z.A., Hashim, M., 2018. The development of soil erosion risk map for Perak, Malaysia. International Journal of Academic Research in Business and Social Sciences, 8 (4), Pp. 1127-1142.

Orgiazzi, A., Panagos, P., 2018. Soil biodiversity and soil erosion: It is time to get married; adding an earthworm factor to soil erosion modelling. Global Ecology and Biogeography, Pp. 1-13.

Palm, J., Van Schaik, N.L.M.B., Schroder, B., 2013. Modelling distribution patterns of anecic, epigeic and endogeic earthworms at catchment-scale in agro-ecosystems. Pedobiologia, 56, Pp. 23-31.

Panagos, P., Standard, G., Borrelli, P., Lugato, E., Montanarella, L., Bosello, F., 2018. Cost of agricultural productivity loss due to erosion in the European Union: From direct cost evaluation approaches to the use of macroeconomic models. Land Degradation & Development, 29, Pp. 1-14.

Peres, G., Bellindo, A., Curmi, P., Marmonier, P., Cluzeau, D., 2010. Relationship between earthworm commmunities and burrow numbers under different land use systems. Pedobiologia, 54, Pp. 37-44.

Pimentel, D., 2006. Soil erosion: A food and environmental threat. Environment, Development, and Sustainability, 8, Pp. 119-137.

Pinard, M.A., Barker, M.G., Tay, J., 2000. Soil disturbance and post logging forest recovery on bulldozer paths in Sabah, Malaysia. Forest Ecology and Management, 130, Pp. 213-225.

Rao, S.V., 2011. Different land use effect on earthworms at SAFE project site in Sabah, Borneo. Nottingham Trent University, Pp. 62.

Reynolds, G., Payne, J., Sinun, W., Mosigil, G., Walsh, R.P.D., 2011. Changes in forest land use and management in Sabah, Malaysia Borneo, 1990 – 2010 with a focus on the Danum Valley region. Philosophical Transactions of the Royal Society B, 366, Pp. 3168-3176.

Ruiz, S.A., Or, D., 2018. Biomechanical limits to soil penetration by earthworms: direct measurements of hydroskeletal pressures and peristaltic motions. Journal of the Royal Society Interface, 15, Pp. 1-14.

Sayer, A.M., 2006. Pipeflow as a storm runoff process in small catchments in Sabah. PhD thesis.

Shipitalo, M.J., Le Bayon, R.C., 2004. Quantifying the effects of earthworms on soil aggregation and porosity. In: Earthworm Ecology. CRC Press LLC., Pp. 183-200.

Steffan, J.J., Brevik, E.C., Burgess, L.C., Cerda, A., 2017. The effect of soil on human health: an overview. European Journal of Soil Science, Pp. 1-13.

van Schaik, L., Palm, J., Klaus, J., Zehe, E., Schroder, B., 2014. Linking spatial earthworm distribution to macropore numbers and hydrological effectiveness. Ecohydrology, 7, Pp. 401-408.

Vishwakarma, A., Yadav, S., 2017. A contribution to earthworm diversity of Central India (Madhya Pradesh) in: Earthworms types, roles and research. Nova Science Publishers. New York, Pp. 217.

Waidi, S., 1991. Hillslope hydrology, hydrogeomorphology and hydrochemistry of an equatorial lowland rainforest Danum Valley, Sabah, Malaysia. University of Manchester. MSc Thesis, Pp. 408.

Waidi, S., Meng, W.W., Douglas, I., Spencer, T., 1992. Throughfall, stemfall, overland flow and throughfall in the Ulu Segama rain forest, Sabah, Malaysia. Philosophical Transactions of The Royal Society Biological Sciences, 335, Pp. 389-395.

Walsh, R.P., Newberry, D.M., 1999. The ecoclimatology of Danum, Sabah, in the contect of the world's rainforest regions, with particular reference to dry periods and their impact. Philosophical Transactions of the Royal Society Biological Sciences, 354, Pp. 1869-1883.

APPENDIX

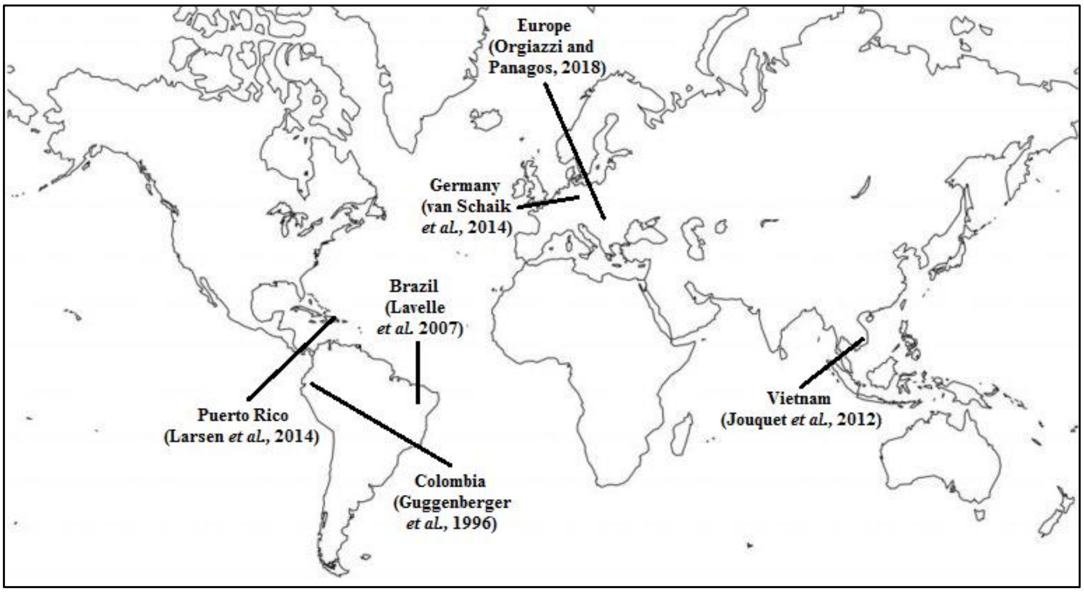

Figure 1. Geographical illustration of past studies conducted, related to earthworms on hydrology