

Quantifying crop vulnerability to ash fall



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Abstract

Volcanoes can significantly affect rural livelihood. Volcanic active regions are endowed with fertile soils that typically develop from ash deposits emplaced during explosive eruptions. As such, these regions are often intensively cultivated and densely populated. They feed about 10 % of the world's population. However, if volcanic activity is the source of these fertile soils, it also poses a serious threat to agriculture. Ash emissions can be dispersed across millions of square kilometers of agricultural land, potentially reducing agricultural production by inflicting significant damages to crops. This results in direct economic loss to farmers, which can cascade along the entire value chain, affecting agricultural growth and rural livelihoods. The type and severity of impacts to agricultural systems from volcanic eruptions are dependent on both the intensity of ash fall and crop vulnerability. Therefore, it is necessary to understand and quantify the relationship between these two parameters to assess accurately ash impact on crops and thus, to better manage the risk of crop yield loss. The objective of this work is to contribute to provide vulnerability data of different crops when exposed to ash fall in controlled conditions. To do so, we simulated the deposition of volcanic ash on five crops, namely cabbages, lettuces, onions, carrots and beans. The plant phenological stage, i.e. seedling, mature, flowering and fruiting, was considered as a key factor dictating the impact intensity for ash loads ranging from 0 to 40 kg m⁻². Our results strongly suggest that incorporating crop vulnerability is mandatory when assessing the risk of crop yield loss. First, this work demonstrates that leafy vegetables such as cabbages are not necessarily more vulnerable to ash fall than root vegetables such as carrots, as previously claimed. Second, cabbages spread with 10 kg m⁻² of ash lost 46% and 10% of its fresh weight at seedling and mature stages, respectively. This highlights that the plant phenological stage is a key factor dictating the intensity of ash fall impact on agriculture. Third, carrot roots exposed to 40 kg m⁻² of ash, became soft after exposure to ash. A such textural change will certainly alter the quality of the product and thus, its sellability on the market. Last, our work has provided information about ash interception and its residence time on vegetation surface, highlighting plant-specific variables such as LAI. Overall, this master thesis provides novel insights into the vulnerability of crops when exposed to ashfall. This paves the way for further investigations aimed at informing the development of adequate agricultural practices that can lower crop yield losses thus decrease the vulnerability of rural communities exposed to volcanic tephra.

Keywords: Ash fall, Volcanic eruption, Tephra, Fragility functions, Crop vulnerability, Risk assessment

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1 Introduction

The number of people living close to volcanoes is rising due to the ongoing increase in global population (Siebert et al. 2010). In order to meet the global population growth, production from agricultural systems is needed (Godfray et al. 2010). A substantial part (at least 10%) of food production is concentrated in volcanically active areas where weathered volcanic ash deposits form fertile agricultural soils (Shoji et al. 1993). Unsurprisingly, regions endowed with volcanic soils are often densely habited and intensively farmed. However, this proximity to volcanoes means also that agriculture is exposed to a spectrum of hazards, the most frequent being the widespread ashfalls (Wilson et al. 2012). Ash can cover thousands of square kilometers of agricultural land, potentially reducing agricultural production by inflicting significant damages to crops (Blong 1984). This results in direct economic loss to farmers, which can cascade along the entire value chain, affecting agricultural growth and rural livelihoods (FAO 2021). The type and severity of impacts to agricultural systems from volcanic eruptions are dependent on both the intensity of ash fall and crop vulnerability (Craig et al. 2016). Therefore, it is necessary to understand and quantify the relationship between these two parameters to assess accurately tephra impact on crops and thus, to better manage the risk of crop yield loss.

For assessing impact and risk to agriculture from ash fall, fragility functions are being developed. These are numeric relationships that link crop yield loss to ashfall intensity, normally represented by the ash deposit thickness. However, these functions do not integrate crop vulnerability. Furthermore, there is a shortage of reported examples of loss to agriculture from ash fall. Therefore, predictions of the impact of ash on crops are not accurate. Several authors emphasize the need to improve fragility functions as they constitute a major knowledge gap (Wilson et al. 2007; Jenkins et al. 2014; Craig 2015).

The aim of this work is to contribute to provide new vulnerability data on different crops after exposure to ashfalls. In order to achieve our objective, two separate greenhouse experiments were carried out. In the first experiment, we simulated ash deposition on five different crops, including cabbage, lettuce, bean, onion and carrot. The plant's phenological stage, i.e., seedling, mature, flowering and fruiting, was considered as a key variable dictating the impact intensity for ash loads ranging from 0 to 40 kg m⁻².

2 State of the art

2.1 Volcanoes and agriculture

2.1.1 Colocation of volcanoes and agriculture

Volcanic eruptions can significantly affect the livelihood of surrounding populations. Because volcanic soils are fertile, they are often being used for agricultural purposes (Cronin et al. 1998, Wilson et al. 2011a, b). Therefore, when volcanic crises occur, the livelihood of farmers can be strongly affected because agriculture is the main income for rural population. For example, during the eruption of Merapi volcano in 2006, farms nearby lost at least 80% of their crop production which represents approximately half of the income of small farms (less than one hectare) (Wilson et al. 2007). This tight colocation between volcanoes and agriculture is also the result of global population increase (Cronin et al. 1998, Annen and Wagner 2003).

2.1.2 Volcanic hazard and agriculture

The destructive forces of volcanoes are well-known and can greatly impact agriculture. For example, the eruption of the Tungurahua volcano in 2006 caused agricultural losses estimated at 150 million dollars and affected more than 300,000 people. In developing countries, the agriculture sector absorbs 23% of the total damage and loss caused by natural disasters (storm, earthquake, flood, drought, volcanic eruption and tsunami) (FAO 2021). Half these damages is absorbed by the crop sector (Trujillo, FAO 2015). Volcanic eruption is the second most harmful disaster responsible for 30% of damage and loss in the agriculture sector (FAO 2021). The capacity of the crop sector to absorb losses from volcanic eruptions and the proximity between volcanoes and agriculture make this sector vulnerable to volcanic hazard. Volcanic eruption magnitude is characterized by the volcano explosive index (VEI). This index ranges from 0 to 8 where 0 is non-explosive and 8 is the maximum. The scale is logarithmic.

2.1.3 Volcanic soils

The term "volcanic soil" is commonly used to refer to soils formed on volcanic deposits such as lava or pyroclastic materials, typically tephra fallout (McDaniel et al. 2012). Most of volcanic soils are known as 'Andosols'. Andosols are usually defined as soils containing a vitric or andic horizon starting within 25 cm from the soil surface and being at least 30cm deep in the first 100cm (World Reference Base for Soil Resources 2014).

Volcanic soils are known to accumulate large amounts of organic matter (OM) (FAO 2014, WRB 2014). They are also among the most productive in the world (Shoji et al., 1994, Takahashi and Shoji 2002, FAO 2001, Neall 2008). During eruptions, tephra is dispersed in the atmosphere and deposited on land. Weathering of tephra releases key plant nutrients such as potassium (K), calcium (Ca), sulfur (S) and phosphorus (P). This provides excellent fertility to the soil and therefore allows plants to grow under good conditions (Shoji et al., 1993; Dahlgren et al., 2004). While volcanic soils cover only 124 million hectares on Earth, which is equivalent to 1% of the total land surface (Neall 2009), they have a significant agronomic potential and they feed about 10 % of the world's population (Ping, 2000). In addition, volcanic soils store at least 5% of the global organic carbon.

The fertility of volcanic soils, thus high crop yields, is also due to excellent properties of the soil such as the high-water retention capacity and a significant cation exchange capacity (CEC). Volcanic soils have a CEC ranging from 20 to more than 50 cmol_c kg⁻¹ at pH 7 (McDaniel et al., 2012) compared to typical value of 3.5 to 20 cmol_c kg⁻¹ at pH 7 (USDA soil taxonomy 2014). Secondly, volcanic soils have good water retention properties because its structure allows the creation of capillaries, conferring to the soil a low bulk density and high porosity (Ping 2000). Limited capillaries generally reduce the availability of water to plants and hence can hinder growth (Masujima and Mori 1962, Maeda et al. 1977). High contents of Al and Fe oxyhydroxides also help to stabilize organic matter, which in turn favours micro-aggregation processes (McDaniel et al., 2012). Thirdly, the pH_{H2O} is ranging from 4.8 to 6 which influences the CEC and thus properties of Andosols (Shoji et al., 1994).

2.1.4 Population density

The number of people living close to volcanoes has risen with increases in global population (Siebert et al. 2010). There is more territorial pressure around volcanoes because volcanic soils are fertile and the demand for food production is increasing rapidly (Godfray et al. 2010). Figure 1 shows the link between the global distribution of Holocene volcanoes and human population.

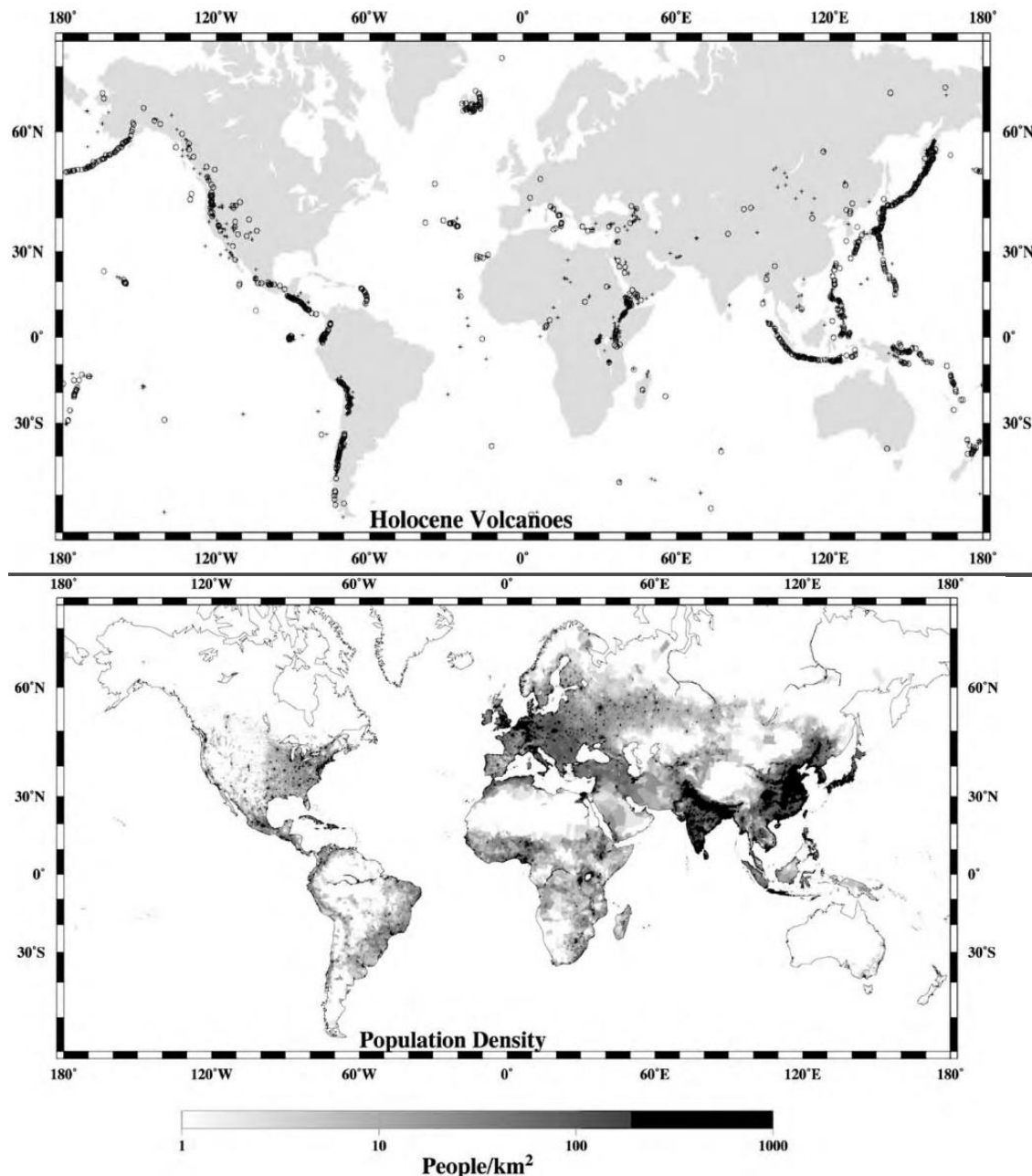


Figure 1. The global distribution of Holocene volcanoes and human population. (Small C. and Naumann T. 2001). Active volcanoes are shown as circles and Holocene volcanoes without historical eruptions are shown as crosses.

Table 1 indicates that developing countries (for example, Indonesia and México) have the highest potential risk for residents near volcanoes (up to 100km radius from volcanoes). This table also shows that more than 53 million people reside within a VPI_5^1 radius. At this distance, people are subject to potentially lethal volcanic effects from even small to moderately large eruptions (VEI 2-3).

¹ The LandScan population dataset (2010) produced by the Oak Ridge National Laboratory was applied to the Smithsonian Holocene volcano database to calculate a Volcano Population Index (VPI) surrounding volcanoes at radius of 5, 10, 30, and 100 km.

Table 1. Volcano Population Index (VPI) data by region. Volcanoes with post-1500 eruptions as a proxy for “historically active” volcanoes. Holocene volcanoes exclude those with uncertain Holocene eruptions. Totals may include residents of the adjacent region living within the pertinent radius of a region’s volcano (Siebert et al. 2010).

Volcanoes with Post-1500 AD Eruptions (n = 589)							
VPI ₅	Popl	VPI ₁₀	Popl	VPI ₃₀	Popl	VPI ₁₀₀	Popl
Region		Region		Region		Region	
Mexico/Central America	8,963,970	Mexico/Central America	10,067,371	Indonesia	48,543,028	Indonesia	173,900,211
Philippines & SE Asia	2,588,904	Indonesia	4,947,238	Mexico/Central America	24,192,929	Japan	80,710,010
Europe	2,384,784	Philippines & SE Asia	3,463,392	Philippines & SE Asia	10,651,359	Philippines & SE Asia	73,743,688
Indonesia	2,111,700	Europe	2,802,081	Japan	9,703,526	Mexico/Central America	73,584,057
Arabia/Indian Ocean	1,360,511	Arabia/Indian Ocean	1,360,511	Europe	6,002,350	Africa	41,427,447
Holocene Volcanoes (n = 1295)							
Mexico/Central America	12,855,939	Mexico/Central America	15,073,682	Indonesia	63,540,182	Indonesia	179,374,526
Philippines & SE Asia	8,291,857	Indonesia	10,051,210	Mexico/Central America	40,215,827	Philippines & SE Asia	110,799,197
Indonesia	5,895,487	Philippines & SE Asia	9,969,791	Philippines & SE Asia	31,817,156	Africa	99,846,719
Arabia/Indian Ocean	5,637,008	Africa	6,584,494	Africa	19,636,196	Japan	93,601,463
Africa	5,377,753	Arabia/Indian Ocean	5,641,014	Japan	13,800,588	Mexico/Central America	89,104,387

Figure 2 illustrates that about 753 million people live within a VPI₁₀₀ radius and most of this population is living adjacent to the most active volcanoes (those with more than 1000 cumulative years active) (Siebert et al. 2010).

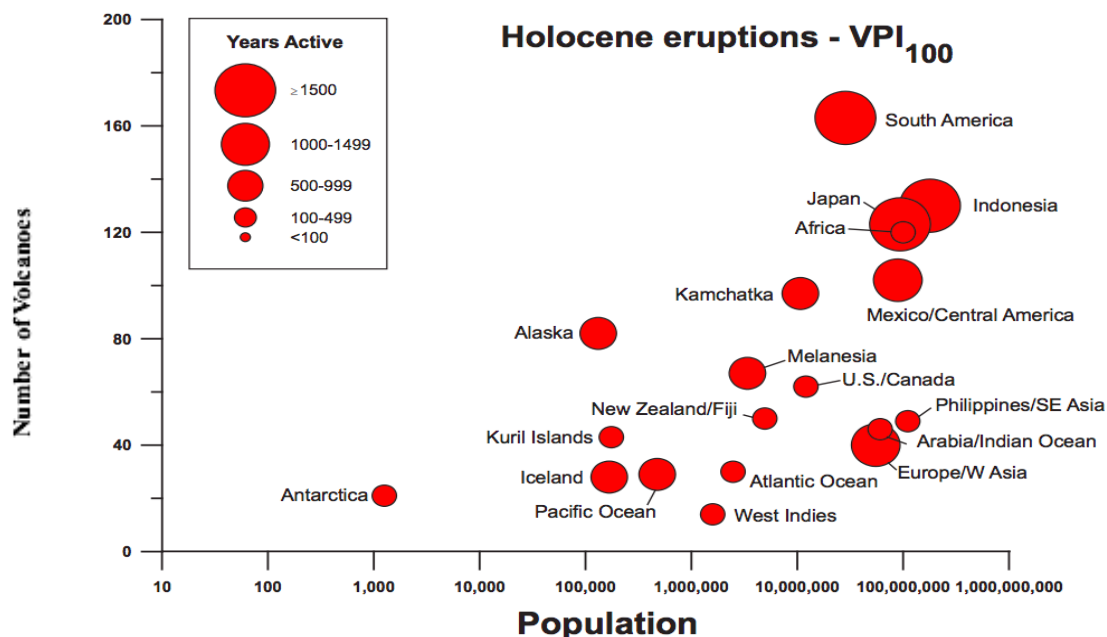


Figure 2. Regional population data for Holocene volcanoes at 100 km radius. Circle size indicates number of cumulative Holocene years active within each region (Siebert et al. 2010).

2.2 Tephra impact on crops

2.2.1 Tephra formation and properties

Tephra is defined as a pyroclastic material (fragments of juvenile magma and lithic rocks) ejected during an eruption (White and Houghton 2006). Tephra has a particle size ranging

from $<63\ \mu\text{m}$ up to $>2,000\ \mu\text{m}$ diameter. It has a broad range of physical and chemical properties because of its widely varying modes of formation. The main mechanism of tephra formation is the disruption of juvenile magma (Dingwell 1996). This could occur when there is a rupture of gas bubbles within a brittle or ductile melt (Cashman et al. 2000), when there is too much shearing forces induced by rapid acceleration of magma (Zimanowski et al. 2003), or when magma interacts with water or ice (Morrissey et al. 2000). Tephra could also be derived from eroded lithic rock or older pyroclastic materials. (Macedonio et al. 1994; McGuire 2003).

Tephra has a broad range of chemical and mineralogical compositions. This bulk composition, varying from mafic ($\leq 57\% \text{SiO}_2$) to silicic ($\geq 77\% \text{SiO}_2$), may influence its chemical reactivity when exposed to environmental agents (Bas et al. 1986; Le Maitre et al. 2002). This diverse composition is inherited from the magma and the rocks from which lithics are derived. The major component of tephra is silicate glass but crystal phases (e.g., quartz, feldspars, plagioclases, pyroxenes, olivines, Fe and Fe/Ti oxides) are also present in various proportions.

The tephra surface composition dictates largely chemical reactivity. When water interacts with tephra, various elements can be solubilized. These are typically Ca, Cl, Na and S, but high concentrations of Al, F and Mg are occasionally reported (Luhr et al. 1984; Taylor and Stoiber 1973). These elements usually occur on the tephra surface as sulphates and halides salts (Cronin et al. 2003; de Moor et al. 2005; Delmelle et al. 2007).

The color of tephra varies depending on the concentrations of transition metals such as iron or titanium. These metals determine the absorption of light (Burns 1970). Low-Si, high-Fe tephra tends to develop a dark brown and black coloration (Scholze 1990). On the opposite, high-Si tephra with a low Fe content tends to be whitish in color because it reflects and transmits visible light (Jones et al. 2007). The differences in chemical compositions impact the albedo of a tephra deposit. A Si-rich tephra reflects more solar radiations than an Fe-rich tephra. Thus, based on its composition, tephra may have a significantly higher albedo than terrestrial soils. The degree of wetness may alter this property (Jones et al. 2007).

Particle size is a key characteristic that influences tephra residence time in the atmosphere, water bodies and, to a certain extent, on soil and vegetation surfaces. It also has an impact on the radiative properties and specific surface area of tephra particles (a_s) (Ayrís et Delmelle 2012). Tephra particle size can vary substantially. Silicic eruptions tend to have higher proportions (30% to $>50\%$) of fine particles (63 to $100\ \mu\text{m}$) than mafic eruptions (only a few percent) (Mastin et al. 2009). Powerful explosive eruptions (compared to effusive eruptions)

lead to more magma fragmentation, and thus also to more fine tephra production (Zimanowski et al. 2003). For example, during the eruption of Mt. St. Helens in 1980 (VEI 5), most of the particles ejected in the air had a size between 1 and 100 μm and were still in the air one week later (Cook et al. 1981). In contrast, the 1974 Fuego eruption (VEI 3) produced less than 4% of very fine particles ($<63 \mu\text{m}$) (Rose and Durant 2009; Rose et al. 2008). Furthermore, magma-water interaction enhances the proportion of fine tephra (Wohletz 1986). Lastly, collisions between particles in pyroclastic flow or even within the volcanic plume may alter the initial particle size distribution (Darteville et al. 2002, Rose and Durant 2009). The particle size controls the a_s . Indeed, smaller particles offer a greater surface area-to-volume ratio than larger particles. The specific surface area of tephra partly governs its potential to be chemically reactive. In general, the measured a_s of tephra is $< 2 \text{ m}^2 \text{ g}^{-1}$ (Delmelle et al. 2005; Horwell et al. 2007). It could also be influenced by particle morphology, porosity and texture (Lowell et al. 2004).

2.2.2 Tephra dispersion

During an eruption, tephra is ejected from the volcano up into the atmosphere. The eruptive column (or the plume) that is comprised of mixed magmatic gases and particles rises because it is hotter than the surrounding air and thus, has a comparatively lower density. At some points, the eruptive column will reach neutral buoyancy because the air is getting hotter, so the mixture is getting colder. At this stage, known as the umbrella region, a plume forms and spreads laterally, transporting tephra over hundreds to thousands of kilometers (Figure 3). Finally, tephra will sediment out of the plume as tephra falls.

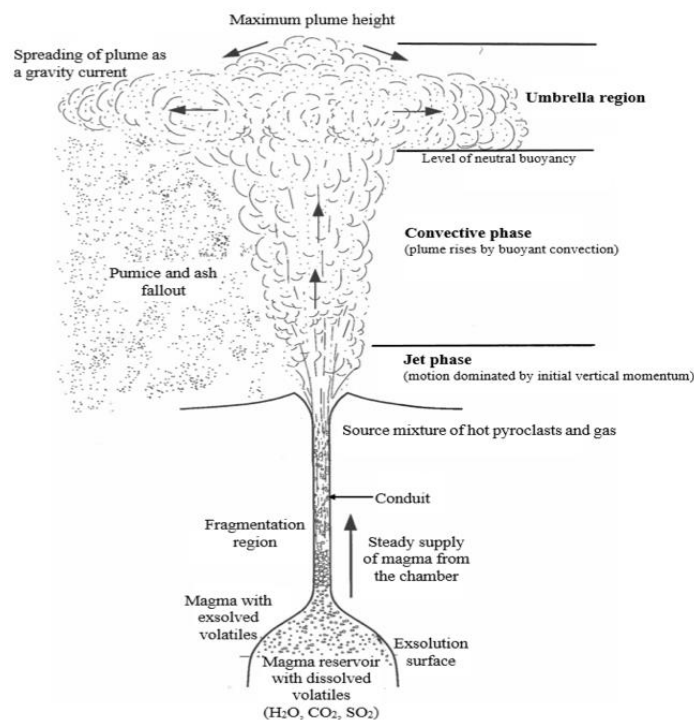


Figure 3. Schematic representation of ascent of the gas- particle mixture in the volcanic plume to the height of neutral buoyancy and dispersion of the volcanic cloud (Tarasenko 2018).

The accumulation of tephra on the ground forms a tephra deposit. After an eruption, the spatial distribution of the tephra deposits can be mapped to produce so called isopach maps (Figure 4). An isopach is a line/contour that delimits the surface area of a tephra deposit characterized by a given thickness. Isopach maps may also be inferred from numerical simulations (Tajima et al. 2013). In general, the thickness and particle size and particle density decrease as the distance from the volcano increases (Blong 1984).

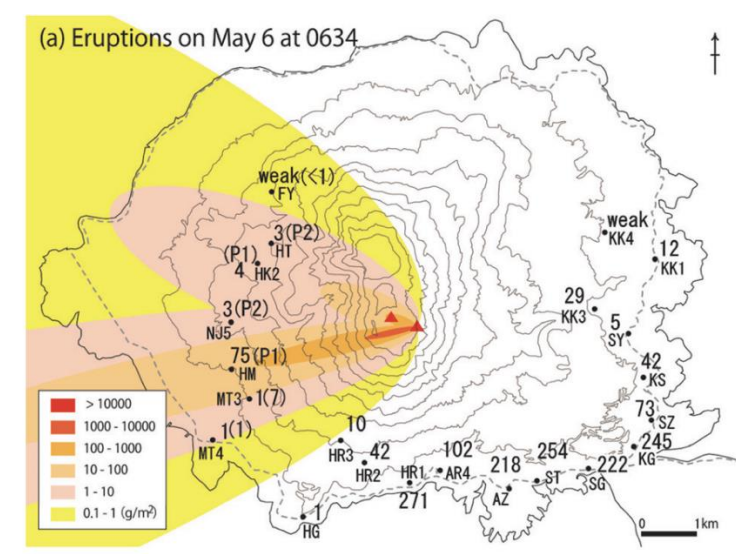


Figure 4. Ellipse-approximated isopach maps for estimating ashfall volume at Sakurajima volcano (Tajima et al. 2013).

2.2.3 Types of impact on crops

Tephra can damage crops throughout three different ways: physically/mechanically, chemically and physiologically. By far, the most common damages are the burial and breaking of stems (Arnalds 2013, Ayris et Delmelle 2012).

The physical and the mechanical effects on plants are the result of the deposition of particles, which will affect crops through loading. The two main processes are the smothering/burial and the breaking of stems and leaves due to the additional weight (Rees 1979). The thickness of tephra impacting physically and mechanically crops can range from 1 up to 500 mm. At 5 mm, less than 50% of the crops is lost. At 50 mm, more than 50% is lost and between 100 and 200 mm, the totally of the crop is lost (Jenkins et al. 2014). Note that these hazard-loss of productivity relationships are based on expert judgement and very few empirical and experimental data. Plants closest to the volcano are generally affected the most because they receive more tephra. Depending on the quantity and particles size (residence time) of tephra on leaves, defoliation may also occur. A tephra deposit can also cause minor damage such as tissue bruising because of particle friction. Whilst this will not on its own be life threatening to plants, it can weaken the tissues in such a manner that it will favor the settling of fungus which will cause damage to tissues. This was observed at Parícutín (Mexico) after the 1943 eruption (Rees 1979). The wind may remove tephra from the plant and thus, decreases its residence time, but it can also create more tephra abrasion due to more friction. Wetting the foliage may also remove tephra but it could also increase the total weight which could lead to more breakages. Furthermore, it could create chemical reactions as described below.

Chemical damage on foliage and fruits may cause injuries due to the release of soluble compounds upon contact with water, such compounds could be halide salts (Cook et al. 1981). For example, chloride on plant surfaces has been shown to result in chemical burns (Rosen and Eliason 2005). Fluoride may have a similar effect (Weinstein and Davison 2004). Lastly, Miller and Hong (1966) reported that tephra from Irazú volcano carried 'sufficient quantities of sulphuric acid to burn the foliage' which resulted in reduced plant growth. It has been shown the tephra contain hydrothermal pyrite (FeS_2) which oxidizes into sulphuric acid upon exposure to rain (Le Guern et al. 1980). This acid could burn leaf cuticles which could increase the susceptibility of necrosis because the foliage will be more vulnerable to desiccation and drought (Percy and Baker 1988; Shepherd and Wynne Griffiths 2006). In addition, acids in contact with the leaf surface may initiate the loss of key plant nutrients such as Ca, Mg and K due to ion exchange (Adams and Hutchinson 1987).

Physiological damage is most of the time a consequence of chemical and/or mechanical damages. For example, plant defoliation due to tephra overloading can lead to less photosynthesis which in turn, will lead to less leaves which means less photosynthesis and so on. The decrease of photosynthesis processes could also be caused indirectly. The tephra particles (and its color) may lower the quantity of radiation reaching the leaves. For example, tephra deposition on pine foliage in excess of 10 g m^{-2} was shown to diminish the radiative flux captured by needles by up to 98 % (Hinckley et al. 1984). In some instances, tephra particles may impede gas exchange by clogging stomates, hence also affecting photosynthesis (Hinckley et al. 1984; Kennedy 1980). Another physiological impact is a reduction in pollination due to tephra-induced injuries to flowers (Rees 1979).

2.2.4 Crop's vulnerability

Crop vulnerability could be defined as the potential crop losses when exposed to hazards (ash thickness) (Blake 2015). The factors influencing the most vulnerability are the physiology, morphology and the phenological stages of the crops (Blake 2015). Therefore, vulnerability is specific to each crop. For example, large horizontal hairy leaves allow more tephra with a greater tephra residence time on it than small vertical waxy leaves. This difference in morphology could lead to structural failures or chemical burns (Smith & Staskawicz 1977). The timing/season when tephra is dispersed on crops also influences crop vulnerability. For example, rice is more vulnerable in late stages of its growth (when flowering) than corn, which is more vulnerable in early to mid-stages (Blake 2015). The importance of plant's phenological stage could also be illustrated with Liliacea (*Veratrum viride*) which is very vulnerable to falling tephra while mature but survives very well when its perennating organs (beginning of its growth) are buried (Antos et Zobel 1985). The amount of tephra and its content in soluble compounds are the third property which plays a role in crop vulnerability. For example, trees such as cocoa tree support better the same amount of tephra than berry bushes such as raspberry bushes. Furthermore, some parts of the plants could be more sensitive than other. In general, fruits are more sensitive to acids and salts than coniferous needles (Haines et al. 1985). Lastly, tephra particle size influences the residence time in the atmosphere and upon vegetables surface. Therefore, finer particles should lead to greater losses (Rose and Durant 2009).

Although vulnerability varies depending on crop type, categories have been made to regroup similar crops. These categories regroup crops which have the same edible thus selling parts. For example, cabbage and lettuce are considered as 'leafy' vegetables because the sellable and edible parts correspond to the leaves. Onions and carrots are 'root' vegetables and beans

are ‘fruit’ vegetables. Root vegetables are supposed to be less vulnerable to tephra falls compared to leafy vegetables which have a more environmentally exposed edible part (Craig 2015).

2.3 Prediction of tephra impact on crops

2.3.1 Fragility function

Fragility functions (figure 5) are numeric relationships used to quantify the vulnerability of crops (Craig et al. 2016). These functions can be used to estimate the risk of crop yield loss. The risk is the probability of an event's negative consequences. The risk assessment is a methodology used to predict the probability of an event's characteristics and the consequences, using a probabilistic hazard model and vulnerability assessment information (fragility function) (UNISDR 2009). Developing quantitative risk models for agriculture is key to forecast potential consequences and thus, to develop pre- and post-eruption strategies that can minimize losses (Smith 2013).

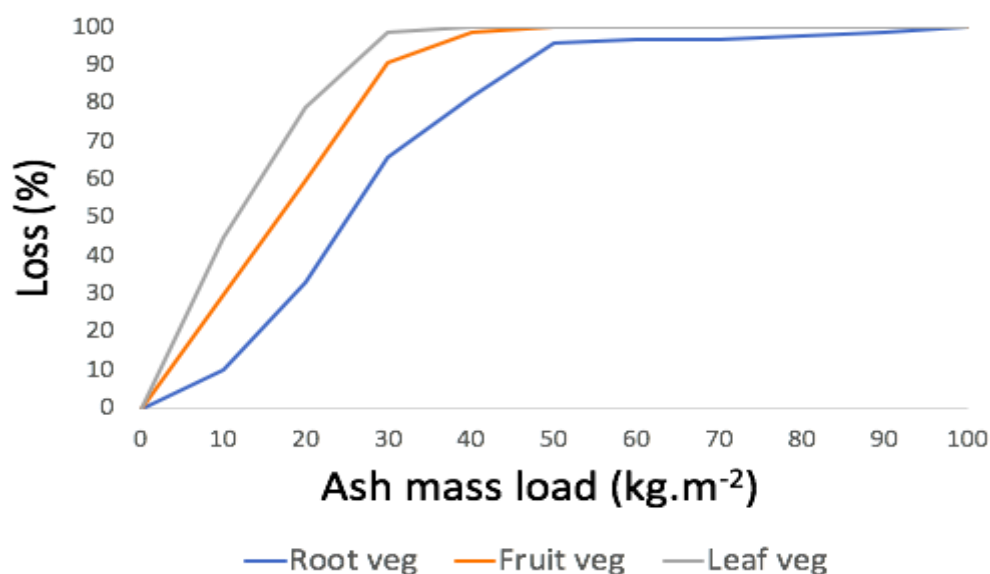


Figure 5. Fragility functions of root (blue), fruit (orange) and leaf (grey) vegetables.

2.3.2 Uncertainties and gaps in knowledge

There are a lot of uncertainties about the quality of existing fragility functions. First, there is a shortage of reported / observed examples of loss to agriculture from volcanic ash fall (at any thickness). Therefore, the prediction of the impact is not accurate, and presumptions must be made. Volcanic ash is also often considered to have fallen in one short, discrete episode, and not followed by additional falls. The notion of time is not integrated with the variables and quantitative risk models for agriculture do not consider crop recovery. Third, for the hazard

intensity, there is no consideration of differences caused by different compositions of ash (silicic versus mafic ash). The role of particle size in modulating the impacts on crops is also ignored. In general, the fragility functions rely on tephra thickness only. Fourth, environmental components such as: wind, rain, topography, are not considered as agents that may modify impacts. Fifth, ash fall may create disruption on electricity, water supply, etc. These effects may impact crop production indirectly. These interdependencies are provided only as estimates of how differing amounts of volcanic ash will lower economic output via incurred losses for farming operations (Craig 2015). Lastly, efforts to integrate crops vulnerability within quantitative risk models for agriculture still need to be done. For the moment, only data on families of vegetables are available (leafy, root, fruiting, cereals, trees). Each crop should have their own fragility function because summarizing plants into categories is too vast and inaccurate. As said before, morphologies, life cycle, etc influence the degree of crop losses. Furthermore, phenological stages of crops are not often considered when eruptions occurred. A first attempt has been made to link seasonality and the loss estimation with a creation of a season coefficient (Craig 2015). But this study is only a first attempt done to fill a gap in volcanic risk estimation techniques and further investigations are needed. Therefore, the objective of our work is to contribute to provide vulnerability data on different crops when exposed to ash fall.

3 Materials and method

Two separate greenhouse experiments were carried out. In the first experiment, we tested the effect of a volcanic ash fall on cabbages and lettuces, whereas we used beans, onions and carrots in the second test. We assessed the plant phenological stage as a key factor dictating the impact intensity for different ash thicknesses. Four phenological stages were chosen: seedling, mature, flowering and fruiting. These are the most important and representative phases in the plant life cycle. The different crop types were selected based on their edible parts. Crops with the same expected vulnerability were paired in order to compare them. The beans should have been paired with rice, but unfortunately the rice culture failed.

3.1 Cabbage and lettuce

3.1.1 Vegetal species, sowing, transplantation and growing conditions

For the experiment, we used the cabbage and lettuce varieties “cabus de Chateaurenard” (*Brassica oleracea*) and “hative d’Heverlée” (*Lactuca sativa*), respectively. They both grow rapidly. Sowing took place on 26 October 2020. Seed trays were filled with 2/3 sieved potting soil purchased from DMC®. This medium is suitable for ensuring plant growth over at least two months. The soil was tamped and 40 holes were dug in each tray. One cabbage seed was placed in each hole, whereas three seeds per hole were used for lettuce. After germination, only the strongest lettuce plants were kept. The seeds were covered up with soils and watered. The trays were protected with a glass frame to minimize evaporation. The lettuces and cabbages were transplanted into 2-L pot once they had four leaves (after 24 days of growth).

The temperature in the greenhouse was 20 °C during the day and 18°C during the night, the photoperiod was set at 16 h using LED lights, the humidity was set at 50% during the day and 75% during the night. Watering was carried out two or three times per week in order to match the plants’ needs. The fertilizer “Blaukorn® Classic 12-8-16(+3+TE)” was used for the rest of the growth (two months after sowing). Based on previous tests and recommendations (<https://www.compo-expert.com/fr-FR/produits/blaukorn-classic-12-8-163te>), 18 g of fertilizer were put per pot every two weeks. Three weeks before harvesting the cabbages, fungi were noticed (Figure 6). To fight against this, the fungicide “Corbel” was used

immediately. A preventive second application was performed four days later.



Figure 6. Head of a cabbage attacked by fungi.

3.1.2 Treatments: experimental set up and ash application

3.1.2.1 Experimental set up

Four different ash thicknesses (mm) were applied on seedling and mature cabbage and lettuce plants. Each treatment was repeated on 16 cabbages and 30 lettuces, for total of 128 and 240 plants, respectively (Figure 7). The total number of cabbage plants was lower than lettuce specimens because the former requires more space for growing, i.e. 50x50 cm for cabbage compared to 30x30 cm for lettuce (<https://www.semaille.com/laitue-pommee/1436-laituehative-d-heverllee-5415166025586.html>) and we were limited in space in the greenhouse.

Mature			Seedling			8m
30mm			20mm		50cm	
10mm			10mm			
5mm			5mm			
30mm			20mm		30cm	
10mm			10mm			
5mm			5mm			
0mm			0mm			
0mm			0mm		50cm	
3m			3m			
Cabbage			Lettuce			
3pots	2pots	3pots	5pots	5pots	5pots	
3pots	2pots	3pots	5pots	5pots	5pots	

Figure 7. Lettuce (light green) and cabbage (dark green) experimental set up.

3.1.2.2 Ash application

The ash used originates from a deposit formed 13,000 years ago by the eruption of the Laacher See volcano in Germany. The initial material has a particle size <3 mm (Figure 8) and is composed of 52,5% of SiO₂, 21,8% Al₂O₃, 9,6% K₂O, 7,8% Na₂O, 2,9% Fe₂O₃, 1,5% CaO, 0,3% TiO₂, 0,2% MgO. It was grinded at the Center Terre et Pierre in Tournais (Belgium).

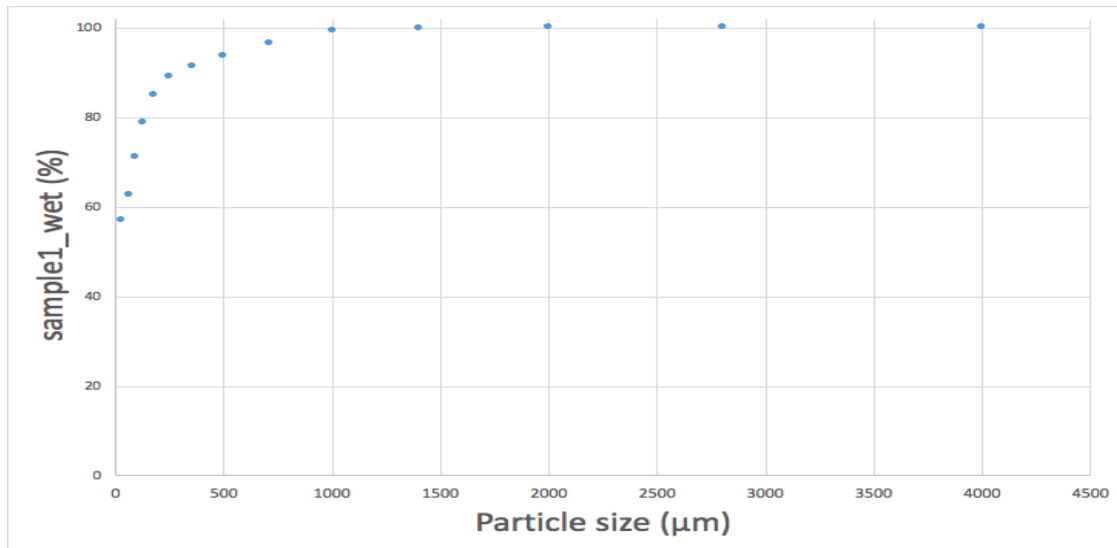


Figure 8. Distribution of the granulometry of the ash coming from a deposit formed 13,000 years ago by the eruption of the Laacher See volcano in Germany.

The ash was spread using a fertilizer/salt spreader modified for our experimental purpose (Figure 9). Briefly, ash was placed inside a container on wheels. When the wheels move, the compartments filled with ash is opened, allowing the release of the ash material. To assess, if the distribution of the ash on the ground was homogeneous, a test was carried out.

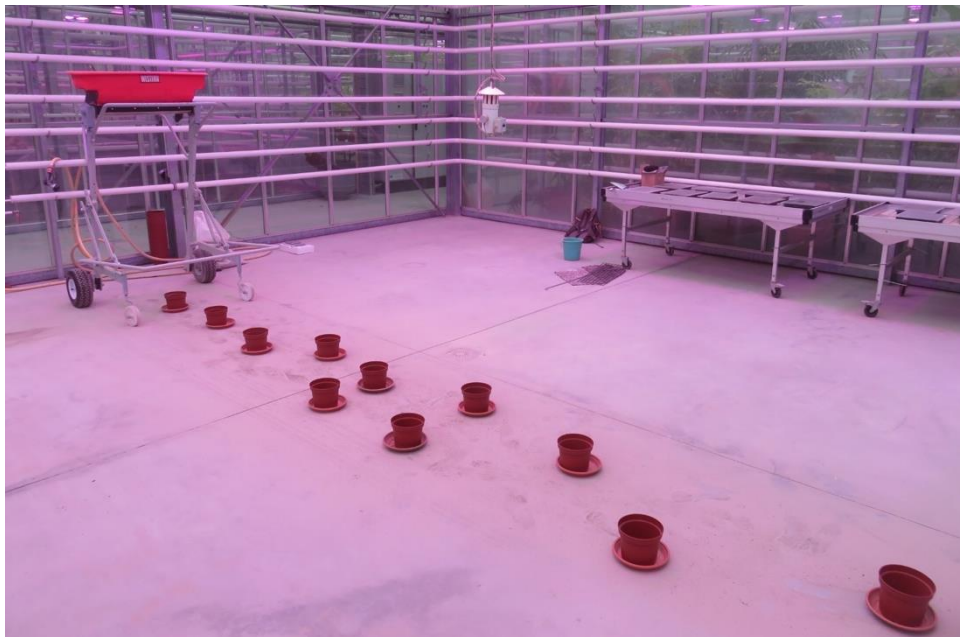


Figure 9. Modified salt spreader used for testing the distribution of the ash on the ground.

Eleven pots across a surface area of 4.5 m² were placed on the ground randomly in order to collect the ash. Each pot was then weighed. The results indicate that ash load was applied uniformly throughout the surface area (Table2).

Table 2. Ash weights resulting from the homogeneity test

Pot	Ash weight (g)
1	1.12
2	1.09
3	1.14
4	1.15
5	1.08
6	1.11
7	1.12
8	1.14
9	1.16
10	1.10
11	1.13

Standard type deviation = 0.03

After ash application, great care was taken not to touch or move the plants in order to avoid the loss of ash particles from foliage. For the same reason, the plants were not watered directly and instead plastic planter boxes were used. Tarpaulins were used during spreading to avoid any contamination of the ash on other treatments.

The first ash application occurred six weeks after sowing, when plants had six leaves and still considered as seedlings (Figure 10). The second application took place 10 and 12 weeks after sowing for lettuce and cabbage, respectively (Figure 11). The two-week difference is because lettuce was starting his senescence process earlier than cabbage.



Figure 10. Seedling cabbages (left) and seedling lettuces (right) before ash application.



Figure 11. Mature cabbages (left) and mature lettuces (right) before ash application.

The percentage of production loss for a range of agriculture types when exposed to various ashfall thicknesses have been reported in a few publications (Jenkins et al. 2014, Thompson et al. 2017, Wilson et al. 2007, Craig 2015). These estimates are based on farmer interviews and expert judgments. Here, they were used as broad guidelines to help deciding the different treatments. According to the aforementioned studies, less than 50% of ground crop production is lost when exposed to 1 to 50 mm of ash. In our experiment, we applied an ash thickness ranging from 0 to 40 mm. For both experiments, we used control groups which did not receive ash. For the seedling stage, both lettuce and cabbage received 5, 10 and 20 mm. When at mature stage, cabbage and lettuce received 5, 10 and 30 mm. More ash was applied to plants at mature than at seedling stage because the crops are supposed to be less vulnerable to ash when mature (Wilson et al. 2007, Craig 2015).

3.1.3 Harvest and data collection

3.1.3.1 Harvest

The harvest of lettuces and cabbages started three and three months and three weeks after sowing, respectively. The stem of the cabbage and lettuce was cut to separate the green part from the senescent leaves. The cabbage was cut a second time to divide its green part into two: the head and the rest. In some cases, ash was still present on the leaves of plants at mature stage. In order to remove the ash, the plants were shaken manually and rinsed with water. Since water rinsing gave the same results than manual cleaning, for practical reasons, it was not adopted.

3.1.3.2 Data collection

The different parts of the plants were put into microperforated bags then were weighed before being dried in an oven at 65°C for four days. When dried, they were weighed once

again. The height and the diameter of the plant were also measured. Alongside quantitative measures, qualitative data were collected. The color, the shape and the size of the leaves were analyzed. We also looked at the general development of the plant such as: the misshaping, dwarf, giant, frail or dead status. Finally, a closer look at where the ash occurs on the plant was taken and we reported plants which died from ash. Finally, pictures were taken to enhance the qualitative data.

3.1.4 Data analysis

The collected data gave us information about the yield and the general development of the crops. The data were treated with the software R. The GGplot2 function available on R software was used to generate graphics. This software was chosen because it is an open source and creates qualitative graphics. Individual specimens which were considered as abnormal before ash spreading were rejected from the data base (Figure 12).



Figure 12. An abnormal cabbage which was rejected from the data base.

3.2 Carrot, onion, bean

3.2.1 Vegetal species, sowing, transplantation and growing conditions

For the experiment, we used the carrot, onion and bean varieties “hative d’Oxhella” (*Daucus carota*), “blanc premier” (*Allium cepa*) and “ratio” (*Vicia faba*) respectively. The sowing took place on 14 and 21 January 2021 for carrots and onions and beans, respectively. The method used was the same than that described above. The onions and beans were transplanted into

2-L pot once they had two (21 days of growth) and six leaves (14 days of growth), respectively. Three onions were placed in each pot. Carrots were transplanted into 2.5-L pots once they had four leaves. Two carrots were put in each pot. Only one bean was transplanted per pot because beans need more space to grow than onions and carrots (<https://www.semaille.com/>, <https://www.agrosemens.com/>). The conditions in the greenhouse, the potting soil and the water supply were the same than those used in the first experiment. The same amount of the same fertilizer was used for the beans two months and two weeks after sowing until the harvest. However, fertilizer was not applied to carrots and onions.

Pests (mites, flies and thrips) started to multiply in the greenhouse from 18 March 2021. To fight against this invasion, a treatment with Neem oil (NEEMAZAL) was applied. An insecticide (ACARAMIK) was also used and a watering containing Nematodes (*Steinernema*) was performed. Bug-scans were also placed to catch flies. A second insecticide application to beans took place on 18 March 2021 (Figure 13).



Figure 13. Bean damaged from mites, flies and thrips.

3.2.2 Treatments: ash application and experimental set up

3.2.2.1 Experimental set up

Four different ash thicknesses (mm) were applied to onions, carrots and beans at seedling and mature stages. For beans, two more phenological stages were added, i.e. flowering and fruiting. Each treatment was repeated on 24 carrots, 30 onions and 24 beans for a total of 210 onions, 168 carrots and 312 beans (Figure 14).

2m		1m	8m		1m	2m		
			Seedling					
5mm			10mm			20mm	32cm	
			Mature					
5mm			10mm			40mm		
			Flowering					
2mm			5mm			10mm		
			Fruiting					
5mm			10mm			30mm		
			Seedling					
5mm			10mm			20mm	16cm	
5mm			10mm			20mm	16cm	
			Mature					
5mm			20mm			40mm		
5mm			20mm			40mm		
			Control					
0mm			0mm			0mm		
6pots	6pots		5pots	5pots		6pots	6pots	
						6pots	6pots	
Carrot			Onion			Bean		

Figure 14. Experimental set up of beans (grey), onions (yellow) and carrots (orange).

3.2.2.2 Ash application

The ash used was the same and was applied using the same protocol as described above. The first ash application to beans occurred one month and one week after sowing, when plants had 12-14 leaves. Two weeks later, plants had 28 leaves and the second application took place. Ash application to plants in the flowering stage occurred two months and two weeks after sowing, when at least half of the population was flowering. The last ash application to beans occurred three months after sowing, when pods were at least three cm long (Figure 15).



Figure 15. Pods before (left) and after (right) ash application (30mm) at fruiting stage.

Ash application to seedling carrots and onions took place two months and two weeks and a half after sowing, when the plants had six and four leaves, respectively (Figure 16 and 17). The second application occurred four months and a week after sowing, when carrots had seven leaves and onions had five (Figure 18).



Figure 16. Seedling onions before (left) and after (right) ash application (5mm).



Figure 17. Seedling carrots before (left) and after (right) ash application (20mm).



Figure 18. Mature carrots and onions before (left) and after (right) ash application (40mm).

Each culture had a control group which did not receive ash. Carrots, onions and beans received 5, 10 and 20 mm of ash at the seedling stage. At mature stage, the carrots and onions were spread with 5, 20 and 40 mm. We did not apply exactly same loadings between the two phenological stages because root crops exposed to ashfall when mature are supposed to be more resistant than crops spread with ash at seedling stage (Thompson et al. 2017). For beans at mature stage, the quantity applied was 5, 10, 40 mm. The thicknesses 5 and 10 mm were chosen to compare the yield crop loss with cabbage and lettuce because they received the same amount of ash at mature stage. 40 mm was applied to assess if at this point, beans will lodge. At flowering stage, 2, 5 and 10 mm of ash were deposited on beans. These loadings are lower than the ones used previously because this phenological stage is supposed to be the most sensitive one (Blake 2015, Wilson et al. 2006). At fruiting stage, beans were spread with 5, 10 and 30 mm of ash. These values are the same than the ones used for the mature stage except that the last value is lower because we wanted to avoid bean lodging.

3.2.3 Harvest and data collection

3.2.3.1 Harvest

The harvest of the onions and carrots started four months after sowing, whereas beans were harvested 3 months and 2 weeks after sowing. The senescent process was beginning for all plants. In order to induce fruiting, all beans were pinched on 5 April 2021. The pinching consisted in cutting off the plant's head (Figure 19). Pods and carrots were collected separately from the leaves and stems. No cleaning was needed.



Figure 19. Pinching of a bean plant.

3.2.3.2 Data collection

Unfortunately, seedling and mature beans were too affected by damages from the pests. This experimental set had to be discarded as only 12 out of the initial 144 bean plants had survived.

The following data were collected: the fresh and dry weight of onions, carrot roots and leaves, beans and pods. We counted also the number of flowers on beans before and after ash application. Same qualitative data were collected than before except that a closer look at flowers was taken.

3.2.4 Data analysis

The software R has also been used to generate graphics thanks to the GGplot2 function.

4 Results

4.1 Cabbages and lettuces

4.1.1 Visual observations

The ash was dispersed almost exclusively on the leaf blade and on the petiole of cabbages and lettuces. Four weeks after ash deposition, some masses of ash were still remaining but only on the base of the blade leaf (Figure 20). A vigorous manual shaking was enough to remove this material. However, this did not remove the fine deposit of ash on the leaf blade. Both crops showed a larger accumulation of ash when more ash was applied. Two weeks before harvesting, on all treatments, some leaf blades started to discolor and turn yellow. At the end of the experiment, the shape of the leaves was unchanged. Concerning the stem, since it does not accumulate ash, neither burns nor stains were observed.

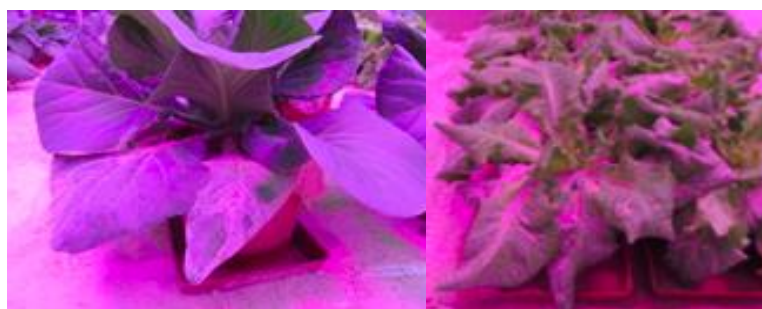


Figure 20. Disposition of the ash on seedling cabbages (left) and seedling lettuces (right) four weeks after application of 10 kg m^{-2} of ash.

Ten days after ash application, new cabbage and lettuce leaves appeared at seedling stage. One week after spreading 30 kg m^{-2} of ash on 30 lettuces at mature stage, 10 plants died (Figure 21). One month after ash application, it was noticed that cabbages treated with ash grew slower than untreated cabbages, but all the specimens survived (Figure 22). At this moment, in all the treatments, the two oldest leaves started to decay (Figure 23). No visual distinctions between mature cabbages and the controls were observed. Whereas, for the lettuces, no distinction could be made between the plant at seedling stage and the controls. At the end of the experiment, half of the cabbages from the seedling group did not form a head, whereas all the control plants successfully did.



Figure 21. Difference in growth between the control group (right) and lettuces spread with 30 kg m⁻² of ash at mature stage (left).



Figure 22. Difference in growth between the control group (left) and cabbages spread with 20 kg m⁻² of ash at seedling stage (right).



Figure 23. Deterioration of the first emerging cabbage (left) and lettuce (right) leaves one month after ash application.

4.1.2 Crop yield

4.1.2.1 Cabbages

The fresh weight of cabbage spread with ash at seedling stage decreases significantly when ashfall increases, whereas the fresh weight of cabbages spread at mature stage does not vary significantly between the four treatments (Figure 24). Based on Tukey test, cabbages spread with 5, 10 and 20 kg m⁻² of ash during the seedling stage show a significant decrease in fresh weight of 34, 46 and 55%, respectively, compared to the control group. Furthermore, the fresh

weight of cabbages spread with 5 and 20 kg m⁻² at seedling stage significantly differs, on average at 20 kg m⁻², 26% of the fresh weight is lost.

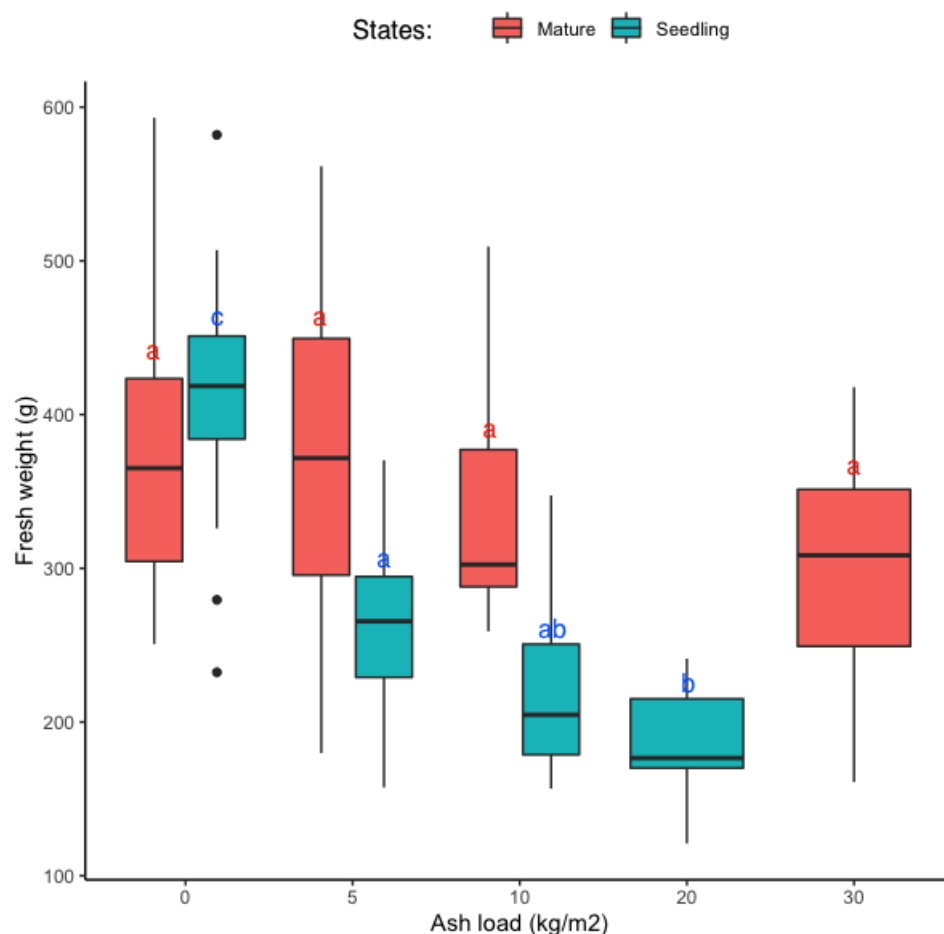


Figure 24. Evolution of the fresh weight of cabbages spread with 0, 5, 10, 20 and 30 kg m⁻² of ash at seedling (blue) and mature stages (red). The letters represent the Tukey test.

The fresh weight of cabbage's heads spread with ash at seedling stage decreases significantly when ash load increases (Figure 25). At 20 kg m⁻², 50% of the seedling cabbages did not produce a head. The average head fresh weight of the treatment 5 kg m⁻² equals to 31 g. This represents a loss of 30% compared to the control group.

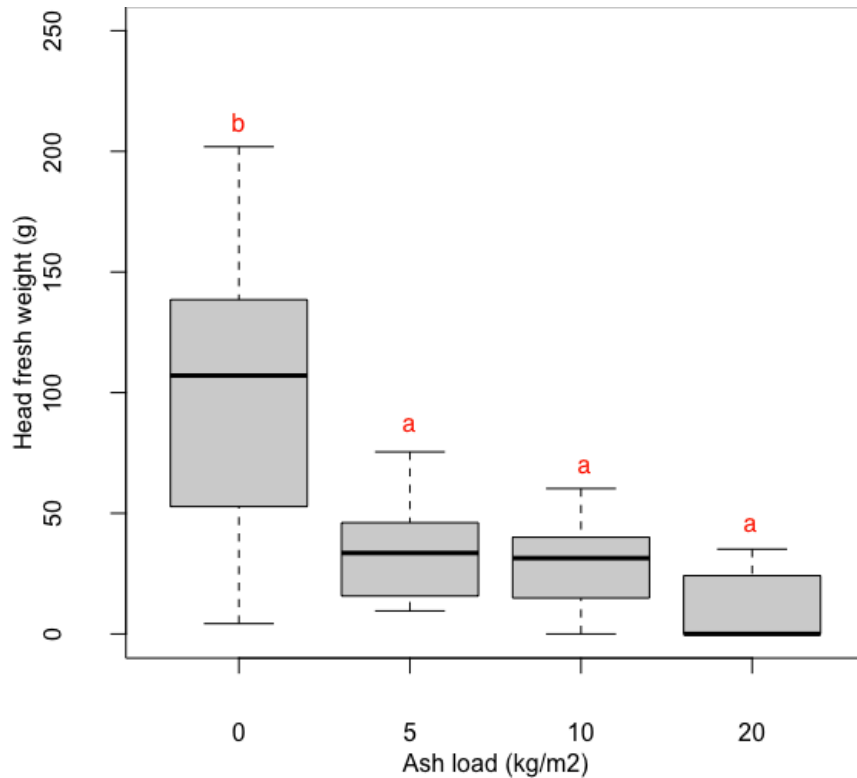


Figure 25. Evolution of the fresh weight of cabbage's heads spread with 0, 5, 10 and 20 kg m⁻² of ash at seedling stage.

The diameter and height of the heads and the leaf span of cabbages spread with ash at seedling and mature stages shrink significantly when ash load increases (Figure 26). The approximated surface (diameter x height) loss of cabbage's heads at both stages, is 55% and 66% for the treatment 5 kg m⁻² and 10 kg m⁻², respectively, when compared to their control group. Concerning the leaf span of both cabbage's stages, 18% is lost when 10 kg m⁻² of ash is applied compared to their respective control group.

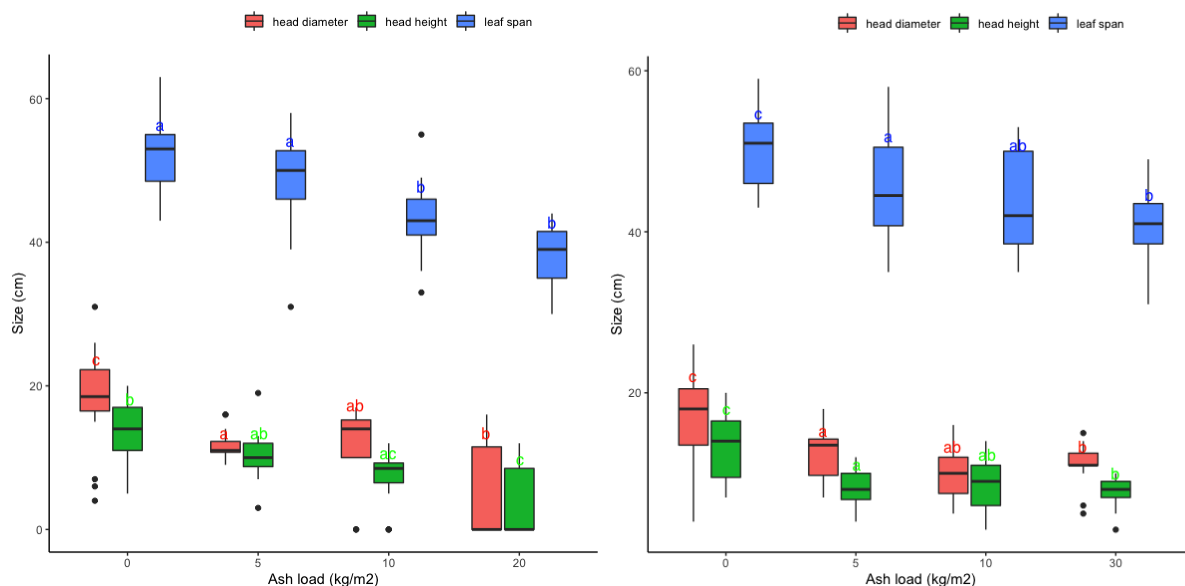


Figure 26. Evolution of the leaf span (blue), head diameter (red), head height (green) of cabbages spread with 0, 5, 10, 20 and 30 kg m⁻² of ash at seedling (left) and mature stages (right).

4.1.2.2 Lettuces

Figure 27 indicates that, based on Tukey test, the fresh weight of lettuces spread with 10 and 30 kg m⁻² of ash at mature stage decreases significantly when compared to the control group. The treatment 5 kg m⁻² also differs significantly from the treatment 30 kg m⁻². The highest fresh weight loss on average is 85 g which represents 66% of the mean fresh weight of control lettuces. On the other hand, the lettuces spread with 20 kg m⁻² of ash at seedling stage lost on average 33% of its fresh weight compared to the control group, which is significant.

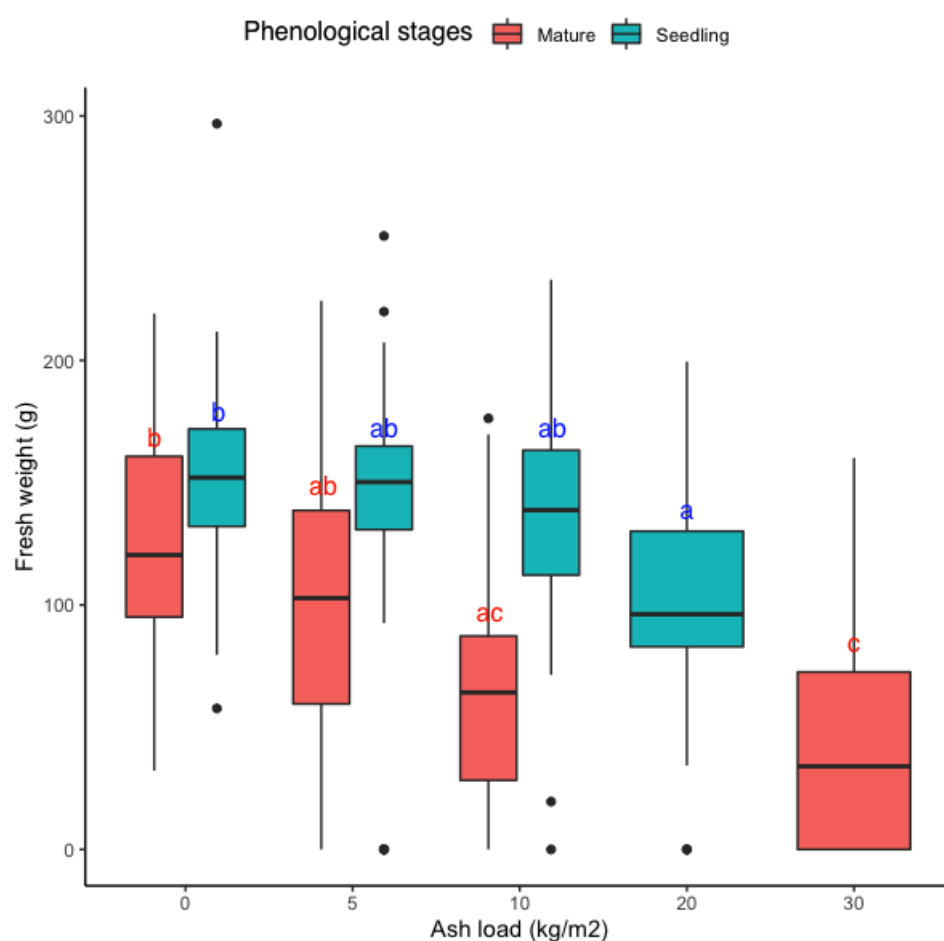


Figure 27. Evolution of the fresh weight of lettuces spread with 0, 5, 10, 20 and 30 kg m⁻² of ash at seedling (blue) and mature stages (red). The letters represent the Tukey test.

The lettuces spread with ash at seedling stage are on average higher than lettuces spread with ash at mature stage. There is no significant distinction between the treatments, except between the treatments 0 and 10 kg m⁻² and between treatments 10 and 20 kg m⁻² at seedling stage. The treatments 0 and 5 differ also from the treatment 30 kg m⁻² at mature stage (Figure 28).

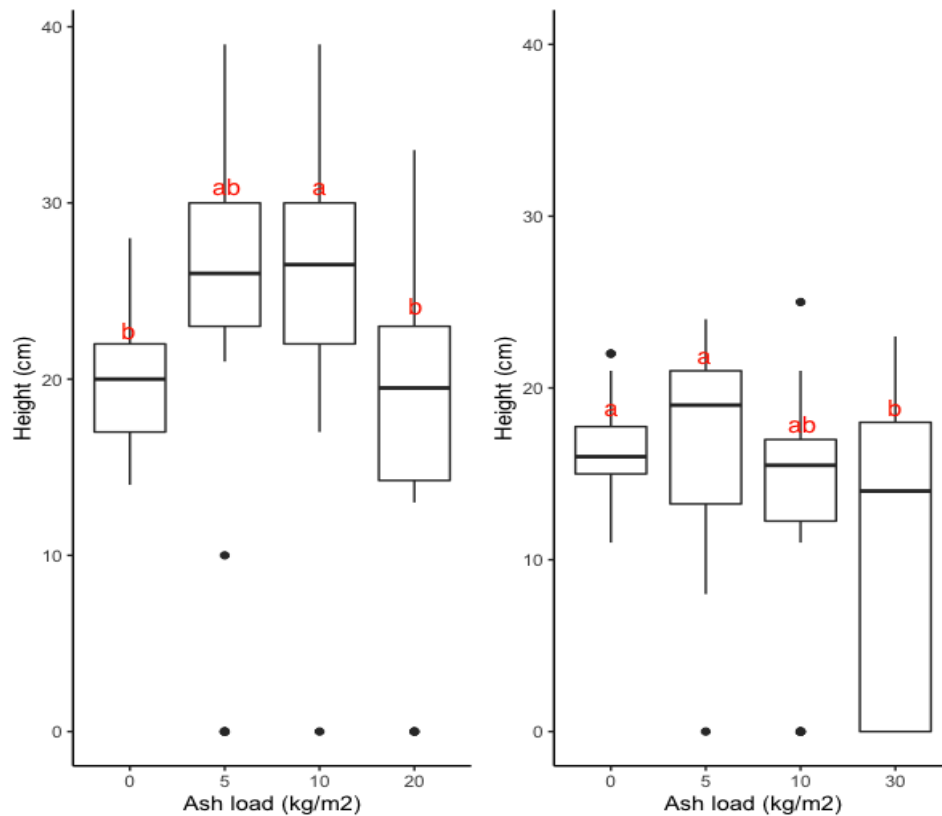


Figure 28. Evolution of the height of lettuces spread with 0, 5, 10, 20 and 30 kg m⁻² of ash at seedling (left) and mature stages (right).

4.2 Beans, carrots and onions

4.2.1 Visual observations of bean plants at the seedling, mature, flowering and fruiting stages

In contrast to cabbage and lettuce plants, an increase in the ash load did not always increase ash retention on leaves. Indeed, at 5 kg m⁻², the amount of ash was already upper than the ash retention capacity of the leaf. Therefore, no clear visual distinction between 5, 10 and 20 kg m⁻² during the seedling stage was observed (Figure 29).



Figure 29. Application of 5, 10 and 20 kg m⁻² of ash (respectively from left to right) on seedling beans.

At 40 kg m^{-2} , the beans bent under the weight of the ash, whereas at 5 kg m^{-2} , it did not (Figure 30). Two weeks after application of 30 kg m^{-2} of ash on the fruiting stages, beans were still curved under this ash load and had buried part, while beans under 20 and 40 kg m^{-2} of ash at seedling and mature stages respectively, managed to overcome the ash layer and grew higher. Unlike cabbages and lettuces, the application of ash on the stems was important (Figure 31).



Figure 30. Bending of beans buried under 40 kg m^{-2} of ash (right) whereas beans under 5 kg m^{-2} stand up straight (left) at mature stage.



Figure 31. Repartition of 10 kg m^{-2} of ash on bean stem at mature stage.

Furthermore, unlike cabbages and lettuces, ash induces discoloration of bean's leaves in all the treatments that received ash. Yellow stains were noticed underneath the ash deposit (Figure 32).



Figure 32. Discoloration of bean's leaves after removing ash layer.

The ash always impacted the flowering stage. Flowers became dried, closed up and eventually fell off (Figure 33). The oldest and opened flowers were the most affected. Two days after the ash spreading, beans produced more flowers.



Figure 33. Opened bean flowers just after application of 2 kg m^{-2} of ash (left) and dying bean flowers two days after receiving the same amount of ash (right).

Ash application also affected pods as some discoloration was observed. Pods which were recovered by ash were light green while the uncovered pods were darker (Figure 34). No ash was found inside the pods. Some seeds were lighter, some darker, some bigger but these differences were observed between seeds belonging to the same treatment (Figure 35).



Figure 34. Light green pods covered by 5 kg m^{-2} of ash (left) and darker green pod which was not (right).



Figure 35. Color difference between two seeds from the same treatment (30 kg m^{-2} of ash at fruiting stage).

4.2.2 Results concerning beans which received ash at flowering and fruiting stages

No results could be obtained for the beans at seedling and mature stages because 92% of the total population died from the pests. The control group was also heavily attacked, with a mortality rate of 12,5% and with 57% of fruit abortion. The fruiting group had the same mortality rate than the control group, but no fruit abortion occurred. The flowering group was less damaged because only 3% of the population died from this invasion. Among all the graphics produced from these two stages, no significant differences between all the treatments could be observed, except between the treatments 2 kg m^{-2} and 10 kg m^{-2} at flowering stage (Figure 36).

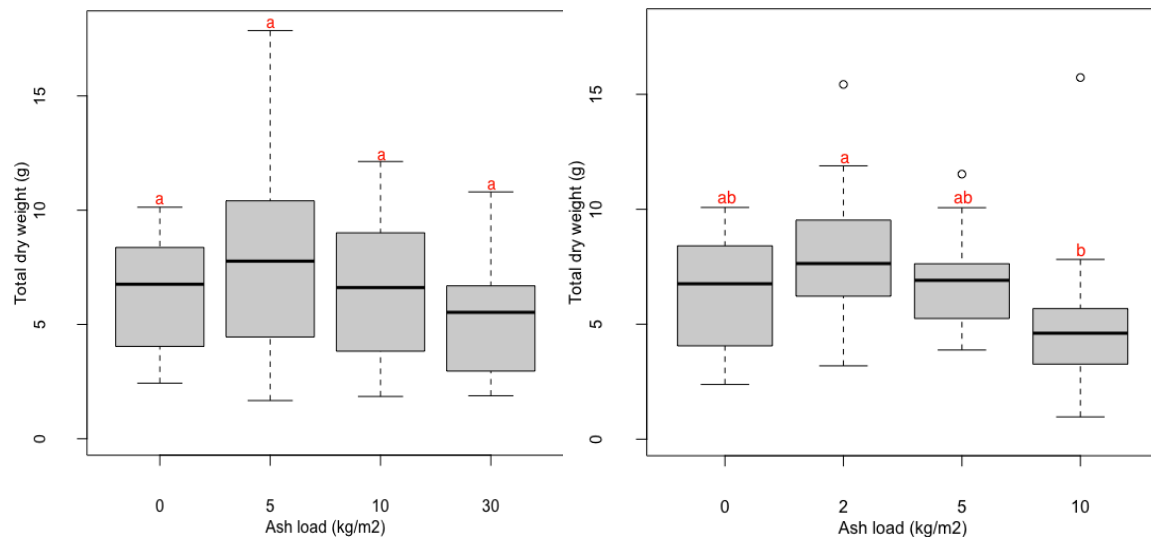


Figure 36. Evolution of the total dry weight of beans spread with 0, 5, 10 and 30 kg m⁻² at fruiting stage (left) and beans spread with 0, 2, 5 and 10 kg m⁻² at flowering stage (right).

Ash application on flowered beans induced more flowering. Indeed, four days after receiving 2 kg m⁻² of ash, 91 new flowers were produced by the population. That is an increase of about 60% of the total flowers. At 5 and 10 kg m⁻² the flower population increases of 66% and 53%, respectively (Table 2). All old flowers felt on the ground four days after the spreading and one-week later almost all flowers died (Figure 37).

Table 3. Number of young and old bean flowers before and after spreading 2, 5 and 10 kg m⁻² of ash at flowering stage.

ash load (kg m ⁻²)	young flowers		old flowers	
	before spreading	after spreading	before spreading	after spreading
2	61	91	77	0
5	44	86	83	0
10	43	48	91	0



Figure 37. Visual distinction between young flowers (left) and old flowers (right).

4.2.3 Visual observations of carrots and onions

Red discolorations occurred on carrot's roots and stems, although these also were observed for specimens in the control group (Figure 38). The shape of the carrot roots varied from a triangle to something more curved, but all the treatments showed this particularity (Figure 39). However, the texture of the roots was different between the control group and the mature group which received 40 kg m^{-2} . At 40 kg m^{-2} , the carrot roots were flabby, whereas the texture of the control was firm. All carrot roots, except those from the control, still had ash on their surface but none was found inside it like onion bulbs. The ash could be removed easily by rinsing them with water. Unlike carrots, the shape, the size and the color of the bulb did not change after ash deposition. Furthermore, no ash was present on the surface of the bulbs (Figure 40). Only a fine deposit of ash was able to stay on the leaves of carrots and onions (Figure 41). When ash was dispersed, most of the ash was falling on the ground. Some ash was found inside the stem of the carrots (Figure 42). Carrot stems started to bend under 20 kg m^{-2} of ash, whereas onions did not bow at any loads. The carrot stems did not straighten up even two weeks after the ash application.



Figure 38. Red discolorations on the root (left) and of the stem (right) of the carrot.



Figure 39. Triangle root shape (left) versus curved root shape (right) of carrots.



Figure 40. Bulb of an onion which received 20 kg m^{-2} of ash at mature stage.



Figure 41. Disposition of 20 kg m⁻² of ash on carrot leaf at mature stage (left) and on onion leaf at mature stage (right).



Figure 42. Ash found inside stems of carrots during the harvest.

4.2.4 Yield results of carrots which received ash at seedling and mature stages

The fresh weight of the carrot roots, at both seedling and mature stages, decreases when the ash load increases (Figure 43). Fresh weight of carrot roots spread with 20 kg m⁻² of ash at both phenological stages, decreases significantly compared to the controls. On average 32% and 25% of the fresh weight were lost at seedling and mature stages, respectively. The fresh weight of the roots at 40 kg m⁻² is the lowest and is equal to 20 g on average. This differs significantly from all the other treatments. On average, roots from control group weigh 48 g. A similar result is obtained for carrot leaves and for the dry weight.

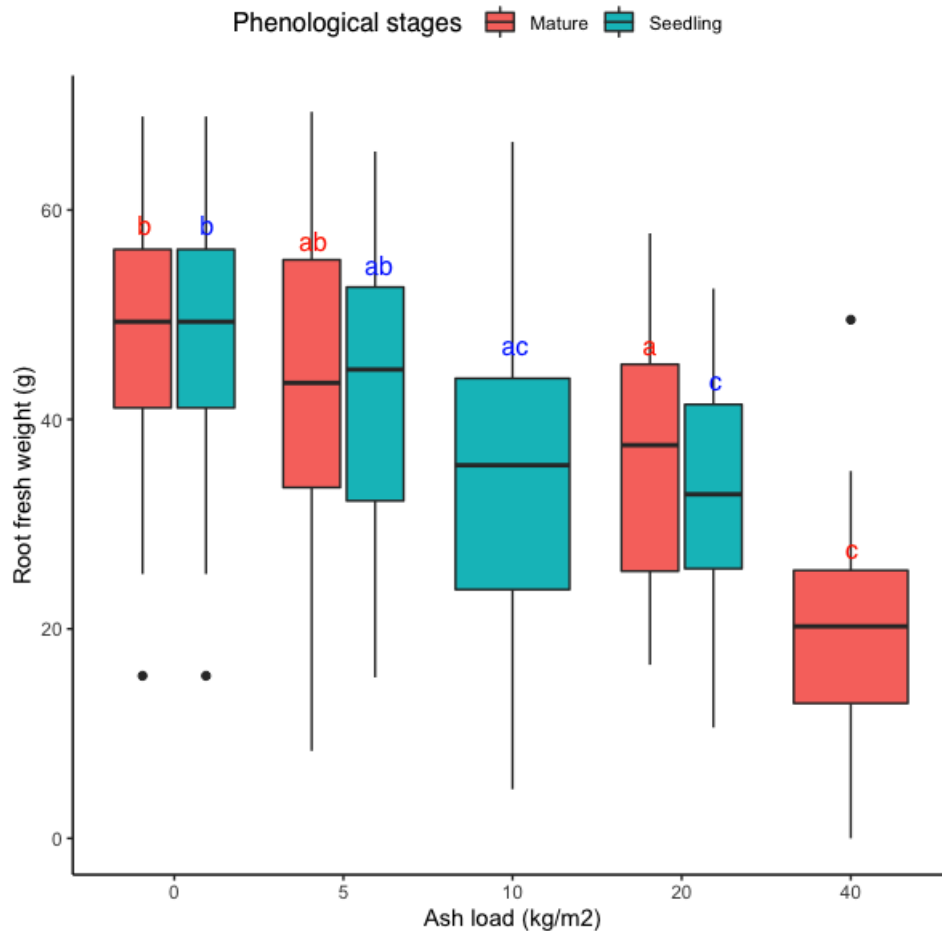


Figure 43. Evolution of the fresh weight of carrot roots spread with 0, 5, 10, 20 and 40 kg m⁻² of ash at seedling (blue) and mature stages (red). The letters represent the Tukey test.

4.2.5 Yield results of onions which received ash at seedling and mature stages

Figure 44 indicates that there is a significant decrease of the fresh weight of onions that received 10 and 20 kg m⁻² of ash at seedling stage compared to the control group. For these loads, the average weight loss represents 30% of the control mean weight. The fresh weight of onions that received 5 and 20 kg m⁻² at mature stage, decreases significantly compared to the control group. Furthermore, there is a significant increase in fresh weight from 5 to 40 kg m⁻². In this case, when we compare the average fresh weight of the control group with the one at 5, 20 and 40 kg m⁻², there is a loss of 32%, 14% and 0.8%, respectively. For mature onions, more ash load does not mean larger fresh weight loss.

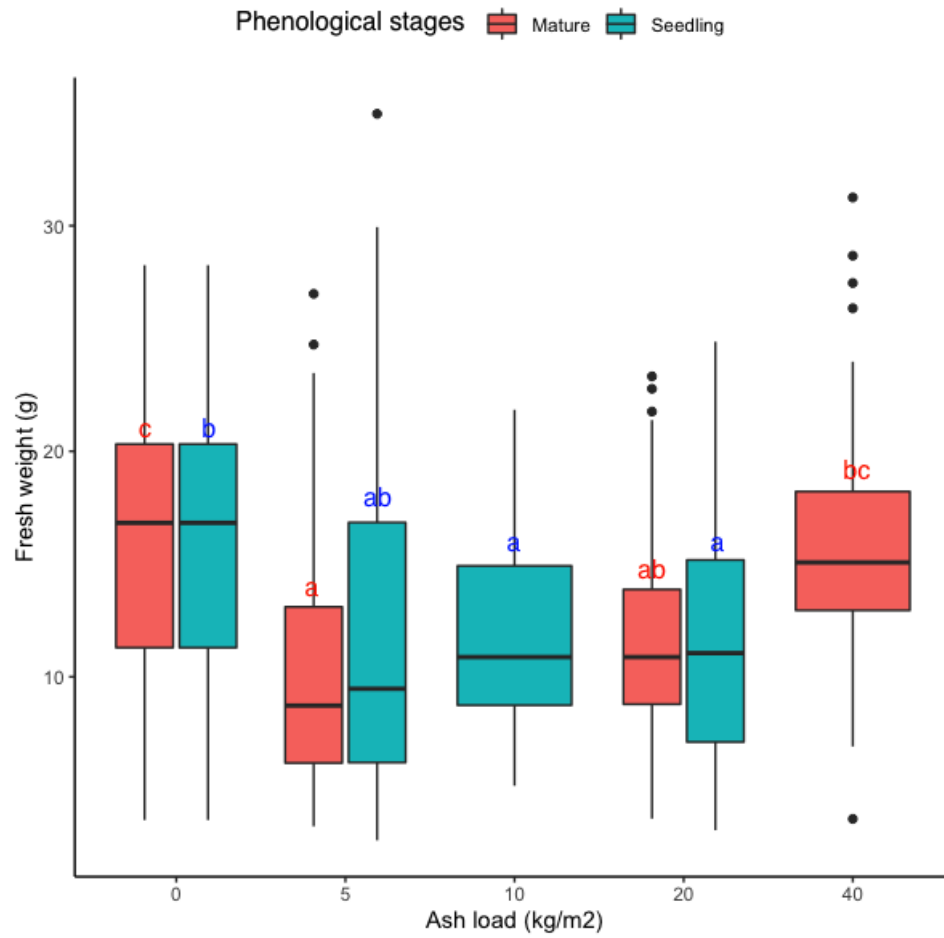


Figure 44. Evolution of the fresh weight of onions spread with 0, 5, 10, 20 and 40 kg m⁻² of ash at seedling (blue) and mature stages (red). The letters represent the Tukey test.

5 Discussion

5.1 Ash deposition on vegetation surfaces

5.1.1 Ash interception

Before reaching the ground, ash is intercepted by crop canopy foliage. Accordingly, the foliages of carrot, bean, onion, lettuce and cabbage plants were covered by ash, although not in the same proportions (Figure 16, 17, 18, 20, 29, 41). The leaf area index (LAI) is a key parameter that determines the ash interception rate. A dense canopy foliage and large leaf surface areas allow more ash particle to be retained on leaves (Smith and Staskawicz 1977, Cook et al. 1981). For example, LAI of cabbage is about two times higher than that of carrot (Lueling et al. 2021, Viña et al. 2011). This means that cabbages intercept ash better than carrots. Furthermore, the leaf canopy structure and the phenological stages of the plant also influence ash interception. Superposed leaves retain less ash than a staggered leaf arrangement. Plants at later phenological stages capture more ash than plants at earlier stages due to the larger leaf surface area in the former. The surfaces of vegetation provide a major filtration and reaction surface to particles (Smith et Staskawicz 1977). In general, the interception of ash particles ($> 10 \mu\text{m}$) by a surface occurs via impaction (Ayrís et Delmelle 2012). Sedimentation under the influence of gravity and deposition under the influence of precipitation are also mechanisms of deposition of ash particles ($> 50 \mu\text{m}$) on plants (Smith et Staskawicz 1977). Ingold (1971) presented data indicating that leaf petioles are considerably more efficient particulate impactors than either stems or leaf lamina. This corroborates our visual observations made on cabbages and lettuces and beans which indicated that most of the ash was stacked on leaf petioles (Figure 20). This was not observed on carrots and onions. Ash amasses as the ash load increases. When the ash weight becomes too heavy, the ash particles slide off the leaves; they will eventually be intercepted by the stem or lower leaves. For example, carrot stems near the ground were covered by ash (Figure 18). By entrainment, the fallout of ash can carry away ash already present on the foliage. Ash could also be intercepted by fruits or flowers. For example, bean flowers and pods caught ash (Figure 15).

5.1.2 Plant-specific variables influencing ash interception and its residence time on leaves

The interception and residence time of ash on vegetation surfaces depend on different plant-specific variables. All crops had different ash interception and retention capacities (Figure 16, 17, 18, 20, 29, 41). For example, ash spread on lettuces stayed longer than ash spread on

beans. During the harvest, plants like cabbages still had ash on their leaves whereas onion leaves did not (Figure 20, 41).

5.1.2.1 Leaf surface roughness

The roughness of leaf surface plays a crucial role in the interception and retention of the ash. In particular, this concerns the fine ($< 10\ \mu\text{m}$) ash particles (Ayrís et Delmelle 2012). For example, during the eruption of Mt. St. Helens, hair-covered leaves favored the retention of ash (Cook et al. 1981). Surface roughness also mitigates the erosive impact of wind and water, the main natural agents that remove ash from vegetation surfaces (Ayrís et Delmelle 2012). Leaf surface roughness certainly played a role in ash interception and influenced ash residence time on cabbage and lettuce leaves. However, it was probably not the predominant parameter influencing it since lettuce leaves retain less ash than the smooth, waxy cabbage leaves, although the two plants should have similar LAI (Figure 20).

5.1.2.2 Leaf angle distribution (LAD) and leaf shape

The inclination and the shape of the leaves dictate the ash residence time on leaves (Blake 2015, Magill 2013). It also dictates the efficiency of ash interception. Planophile entire ovate leaves like cabbage leaves retain more ash, and for a longer period than erectophile filiform leaves (for example, onion) or palmatisect toothed leaves (for example, carrot). Bean leaf is also planophile but unlike cabbage its shape is elliptic causing less ash interception. Leaf inclination and shape largely explain ash retention on crops (Sword-Daniel 2011).

5.1.2.3 Stem elasticity

Surprisingly, bean leaves did not retain as much ash as expected. Based on leaf shape and morphology, beans leaves should have intercepted and retained less ash than cabbage and lettuce leaves but more ash than carrot and onion leaves. In our case, bean leaves retained approximately the same quantity of ash than carrot leaves (Figure 29, 41, A-1, A-2, A-3). When ash was applied, most of it felt on the ground because of the elasticity of the plant. Bean, carrot and onion plants bent and swang as ash was hitting foliage and this led to ash fallout. Even though the capacity to bend could be a positive think for its ash removal function, at a certain amount of ash, it will cause structural damages (Blake 2015).

5.1.2.4 Plant height

The height of the plant also helps to determine ash interception and residence time on foliage. The canopy foliage of taller growing plants, such as chilies, tomatoes and beans can protect the canopy foliage of low growing plants, such as lettuces because it intercepts first the ash (Wilson et al. 2007). Because of mechanical resistance, higher plants are more often subject to structural failure than lower plants (Wilson et al. 2007). In the event of heavy ashfall (< 50 mm), the overloading of the surface may cause structural failure resulting in early abscission of leaves and collapse of branches, thus shortening ash residence time (Cook et al. 1981).

5.2 Vulnerability of the crops when exposed to ashfall

Figure 45 illustrates that all crops lose fresh weight when exposed to ashfall, except onions spread with ash at mature stage. The crop loss (fresh weight) varies as a function of ash load, but also between the different crops at different phenological stages. Mature lettuces are more vulnerable to ashfall than seedling lettuces whereas, for cabbages it is the opposite. Concerning carrots and onions such generalities cannot be made.

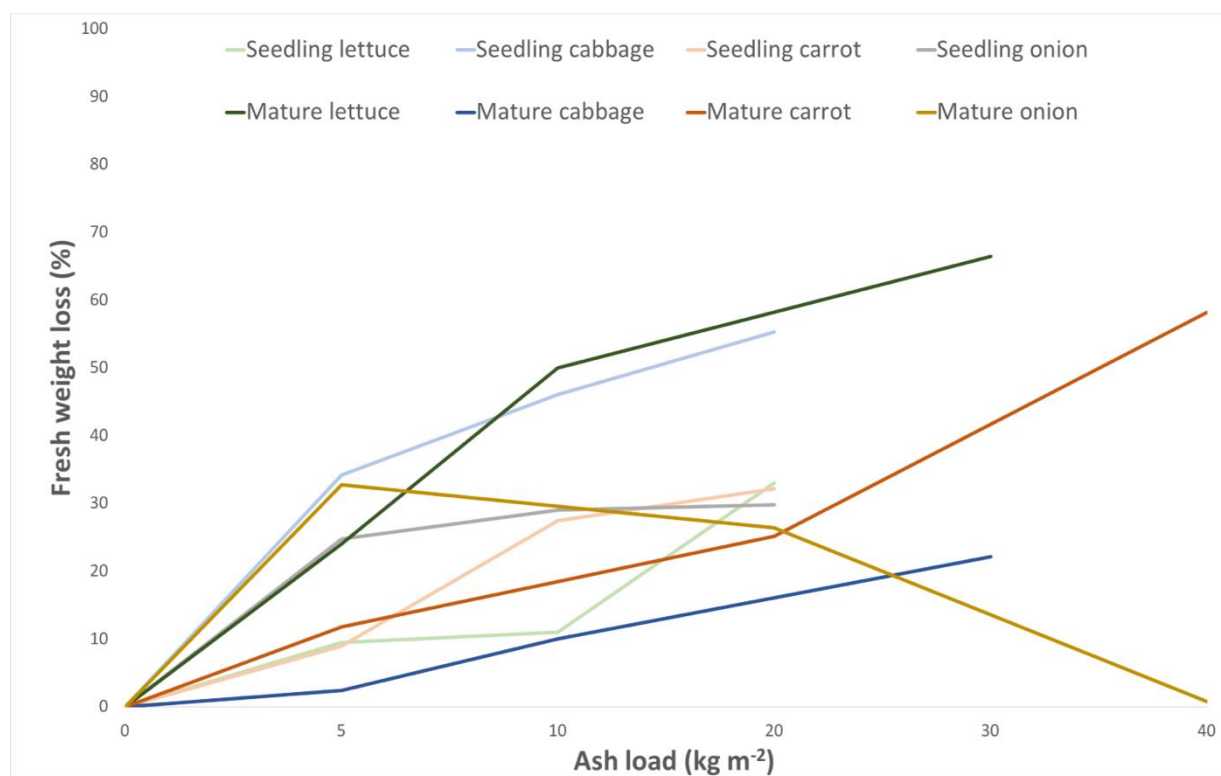


Figure 45. Evolution of the fresh weight loss of seedling and mature onions (grey and dark yellow), seedling and mature carrots (light and dark orange), seedling and mature lettuces (light and dark green), seedling and mature cabbages (light and dark blue) when exposed to 0, 5, 10, 20, 30 and 40 kg m⁻² of ash.

5.2.1 Comparison of crop yield loss

Cabbages spread with ash at mature stage show the lowest fresh weight loss among all the crops up to $\sim 30 \text{ kg m}^{-2}$. This result was not expected since leafy vegetables are always the most vulnerable crops to ashfall reported in literature (Cronin et al. 1998, Wilson et al. 2007, Wilson et al. 2011, Craig et al. 2016). From 10 to 30 kg m^{-2} , mature lettuce shows the highest fresh weight loss. All curves increase when ash load increases, except for mature onion which shows a significant decrease from 5 to 40 kg m^{-2} (Figure 45).

5.2.1.1 Crop yield loss of cabbages and lettuces

The average fresh weight losses are 46% and 11% for cabbages and lettuces, respectively, spread with 10 kg m^{-2} at seedling stage, whereas the losses are 10% and 50%, respectively, when the mature stage plants receive the same ash load (Figure 45). This highlights that each culture has its own vulnerability, even when they have similar consumable and sellable parts. Furthermore, this confirms what Craig et al. (2016) affirmed about the importance to consider crop phenological stages when quantifying crop vulnerability to ashfall. Mishra and Shukla (1986) demonstrated that fly ash dispersed on maize and soybean leaves can impede plant growth and decrease dry matter production in different proportions. Maize formed more leaves than soybean and thus, had a higher dry matter production. Based on visual observations, lettuces grew more leaves after ash dispersion than cabbages, when both plants were spread with 20 kg m^{-2} at seedling stage. This suggests that lettuces recover quicker than cabbages from ash damage at seedling stage. Even though the head size and leaf span of cabbages decrease when ash load increases, this effect cannot explain the decrease of cabbage fresh weight (Figure 26). For example, at 10 kg m^{-2} , the heads lose 66% of their size and the span is shortened by 18%, independently of their stages. Whereas the average cabbage fresh weight loss is about 46% and 10% when 10 kg m^{-2} of ash is applied at seedling and mature stages, respectively. If the head size or leaf span were the parameters determining the overall fresh weight loss, cabbages spread with 10 kg m^{-2} at mature and seedling stages should have lost the same amount of weight. The height of lettuces spread at mature stage do not vary significantly but the fresh weight does (Figure 28). This means that the height does not explain the fresh weight loss. Different parts of the same plant could also react differently to ash load (Wilson et al. 2011). Fresh weight of cabbage heads spread with 5 kg m^{-2} at seedling stage decreases of about 66% whereas 34% is lost for the overall plant (Figure 25). The supposed sensitivity of cabbage heads to ash is particularly a problem because heads are the consumable part and a source of income for farmers. Furthermore, cabbages spread with 5 kg m^{-2} at mature stage also show a decrease of 66% in the fresh weight of heads (Figure A-4).

This means that this loss is neither linked to the phenological stage nor linked to damage state of cabbages spread at seedling stage which could have been too damaged to form heads.

Wilson et al. (2007) estimated that 20% of the leafy vegetables production was lost with signs of ash abrasion and chemical impacts on plants when 2 kg m^{-2} of ash was applied. This ash load was not tested but no signs of burns on lettuces and cabbages were noticed at 5 kg m^{-2} . This could confirm that ash do not directly cause abrasion and chemical damages but needs water for chemical reactions (i.e., hydrothermal pyrite transforming into sulphuric acid) or wind to cause particles frictions. At 5 kg m^{-2} , the fresh weight loss ranges from 2.4% to 34.2% for cabbages and from 9.5% to 24% for lettuces (Figure 45). These ranges include 20% and seems to confirm Wilson et al. (2007)'s estimate. However, when 5, 10 and 30 kg m^{-2} of ash were applied, 90% of the leafy vegetables production was reported to be too damaged to be saleable, because either crops were destroyed or ash removal was so expensive which makes harvesting uneconomical (Barnard 2003). The maximum fresh weight lost is 66.5% for lettuces spread with 30 kg m^{-2} at mature stages (Figure 45). In addition to the cost for washing, this 23.5% crop loss difference between the experiments could be explained by the fact that our lettuces grew in controlled conditions which protected them from rain and wind. Furthermore, the whole plant fresh weight was measured for lettuce while only its fresh leaves should have been weighed. Indeed, Wilson et al. (2007) estimated the leafy vegetables production loss which concerns only lettuce leaves or cabbage heads.

5.2.1.2 Crop yield loss of carrots and onions

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Concerning the carrot plants, the fresh weight significantly decreases when ash load increases. Compared with the control group, carrot roots spread with 40 kg m^{-2} of ash lost on average more than 50% of fresh weight (Figure 45). The loss is probably linked to the carrot's flabby texture. It has been reported that ash may initiate the loss of key plant nutrients such as Ca, Mg and K due to ion exchange (Adams and Hutchinson 1987). These nutrient losses may have triggered physiology and biochemical reactions which could have softened carrot roots. Water loss of roots do not explain by itself this texture change because roots spread with 40 kg m^{-2} lost 45% of its dry weight compared to the control group (Figure A-5). This means that only 5% of the root fresh weight loss is due to water loss. In this case, based on four different ash loads, we cannot say that there is a phenological stage more vulnerable than another (Figure 45). Indeed, on average the difference between the fresh weight of carrot roots spread with 5 kg m^{-2} at seedling and mature stages is equal to 3% whereas, for lettuces and cabbages at the same ash amount, this difference is equal to 15% and 32% respectively. At 20 kg m^{-2} , this difference equals to 7% for carrot roots. Thus, the yield differences between

carrots spread with ash at the seedling and mature stages are much less significant than the differences noticed for lettuce and cabbage at different phenological stages. This result could be explained by leaf morphology. In contrast to cabbage and lettuce plants, the LAI between seedling and mature-stage carrots does not evolve significantly. Lueling et al. (2021) showed that the leaves of cabbages growth significantly during their life cycle. Furthermore, only one additional leaf was produced per carrot from seedling to mature stage, whereas at least six were produced by the lettuce and cabbage plants.

Onions also lost fresh weight when ash load increases, except in the treatment corresponding to 40 kg m⁻² at mature stage (Figure 45). The onions from this treatment weigh significantly more than the ones which received 5 kg m⁻² at mature stage. This increase could be because ash fertilized the crop. This phenomenon has already been observed on rice crop (Jenkins et al. 2014). Surprisingly, onions spread with 5 kg m⁻² at mature stage is the only crop showing significant fresh weight loss compared to its control group (Figure 45). Although, this crop is one of the most vulnerable crops at lower ash load, it's the most resilient to higher ash load when the same phenological stages are compared together (Figure 45). The onion is the only crop showing this fertilizing effect probably because its leaves intercepted less ash, and the crop was less affected by ash. Furthermore, because the onion's leaf surface area is the smallest, more ash felt in the pot. Inside the pot, the ash was wetted which allowed the release and absorption by the roots of key plant nutrients such as potassium, calcium, sulfur and phosphorus (Cronin et al. 1998, Shoji et al. 1993). The low LAI, coupled with the elasticity of the plant, spreading more than 5 or 10 kg m⁻² will not damage the crop further. However, at 5 or less kg m⁻² of ash, the maximum ash retention capacity of onion leaves is not reached, and the ash still could be intercepted. We cannot say which onion stage is the most vulnerable because onions spread with 5 kg m⁻² lost 25% and 32% of their fresh weight, while at 20 kg m⁻², 30% and 26% were lost for seedling and mature stages, respectively (Figure 45). In the case of the 20 kg m⁻² treatment, the seedling stage is more vulnerable than the mature stage, whereas it is the opposite for 5 kg m⁻².

Wilson et al. (2007) estimated that 1% of the root vegetable production was lost with signs of ash abrasion on leaves when 5 kg m⁻² of ash was applied. No signs of burns on carrot and onion leaves were noticed at this loading but the environmental conditions were different. In our experiment, carrot and onion fresh weight losses range from 9% to 32.8% when same quantity of ash was applied (Figure 45). Which means that in any cases, Wilson et al. (2007) underestimated the loss. The authors also estimated that 20% of the root production was lost at 30 kg m⁻², whereas carrots already lost 25% and 32% of its production at mature and seedling stages respectively when 20 kg m⁻² was spread (Figure 45). In our experiments, at the same ash load, 26% and 30% were lost for the onions at mature and seedling stages

respectively (Figure 45). Leafy productions losses were overestimated by Wilson et al. (2007) but these losses could be explained by experiment-controlled conditions whereas, for root vegetables it could not because Wilson et al. (2007) underestimated the production loss compared to what we found. Furthermore, Wilson et al. (2007) only provided yield loss estimations which are not as accurate as calculated losses.

5.2.2 Phenological stage as key parameter influencing crop vulnerability

It has been reported that leafy vegetables are always more vulnerable to ashfall than root vegetables (Craig 2015, Wilson et al. 2007). When the phenological stages are considered, this is not true anymore. Indeed, carrots and onions spread with ash both at seedling and mature stages are more vulnerable to ashfall than cabbages and lettuces spread at mature and seedling stages, respectively. An opposite trend is inferred when the comparison is made for cabbages and lettuces spread with ash at seedling and mature stages, respectively (Figure 45).

5.3 Stresses induced by ashfall

5.3.1 Stress-induced flowering

Ash induced two different reactions on beans at flowering stage. First, it stressed the plant which responded by producing new flowers. This stress-induced flowering has also been reported by Wada et Takeno (2010). Second, it dried and killed the flowers already present (Figure 33). Acids and abrasion damages on flowers were also reported on other crops such as tobacco and chili peppers (Wilson et al. 2006, Craig et al. 2016). After one week, almost all flowers died. When more than 2 kg m⁻² of ash was applied to bean plants, the plant produced less flowers. For example, beans spread with 2 and 10 kg m⁻² produced in four days 91 and 48 new flowers, respectively, whereas the control group did not produce any additional flowers during the same period (Table 3).

5.3.2 Stress-induced growth

The lettuce height slightly increases during seedling stage at 5 and 10 kg m⁻² (Figure 28). This may be the result of ash-induced stress that led to plant growth acceleration, called lettuce bolting. An increase in stem height has been reported following ash deposition (Smith et al. 2010). Lettuces spread with 20 kg m⁻² at seedling stage were smaller than the ones spread with 5 and 10 kg m⁻² of ash. When more ash was applied to lettuces, the plant growth acceleration decreased (Figure 28).

5.4 Ash load can make the crop production unsellable

Farmer income losses are not only caused by crop fresh weight losses (Barnard 2003). Indeed, discolorations, misshaping and size abnormalities can degrade the quality of the crop production. For example, carrots spread with 40 kg m^{-2} became softer. This texture change can make the product unsellable. Furthermore, during the harvest, ash was still present on all crops except for onion bulbs (Figure 40). Thus, a crop cleaning with water is mandatory before being sold. We could not establish a clear link between ash loading and discoloration of bean pods and seeds but if there is one, this could also make the product unsellable because consumers would probably be reticent to buy yellow beans instead of green (Figure 34). Red discolorations of carrot roots are certainly due to light because it was observed on all the carrots and only at the top of the roots which were not always recovered by pot ground (Figure 38). Just as discoloration, changes of the carrot root shape could make the production unsellable (Figure 39). The shape abnormalities could be a consequence of soil compaction and the size of the pot which provided not enough space for two carrots (Poorter et al. 2012). Lastly, ash induced discoloration of bean leaves and was still present on it before harvesting (Figure 32).

5.4.1 Cleaning efforts

For all crops, water cleaning removes all the ash adhering to foliage, but it will cost time and money for farmers. Furthermore, it has been reported that water cleaning could damage crops especially when exposed to fine ash deposits which have a greater adherence to leaves (Blake 2015). If carrot leaves are sold as food for livestock, an additional washing step should be done because masses of ash were found inside (Figure 42).

6 Conclusions

The objective of this master thesis was to investigate and quantify how crop vulnerability characteristics influence volcanic ash fall impacts on agriculture in controlled conditions. The research was undertaken on the basis that accurate, robust risk assessments are required to inform effective disaster risk management in order to reduce the risk of crop yield losses. However, these assessments rely on a limited understanding of crop vulnerability and therefore, should be improved.

Our study has contributed new knowledges to the field. First, it demonstrates that leafy vegetables such as cabbages are not necessarily more vulnerable to ash fall than root vegetables such as carrots, as previously claimed. For example, the fresh weights of carrot, cabbage and onion, except lettuce, spread with 10 kg m^{-2} of ash at seedling stage decreases significantly compared with their respective control groups. This implies that carrots are more vulnerable to ash fall than lettuces. Second, each crop shows different yield losses at different ash loads. This highlights that each crop has its own vulnerability even when they have similar consumable and sellable parts. Third, the plant phenological stage is a key factor dictating the intensity of ash fall impact on agriculture. For example, the fresh weight loss of cabbage spread with 10 kg m^{-2} of ash is 46% and 10% at seedling and mature stages, respectively. This loss difference makes the cabbage one of the most vulnerable crops among the four crops (i.e., carrots, lettuces, beans and onions) exposed to ash at seedling stage. However, cabbage is one of the most resistant crops at mature stage. Fourth, a greater ash load increases crop yield loss, except for onion spread with 40 kg m^{-2} of ash at mature stage. This exception illustrates that ash could have a fertilizing effect. Fifth, plants may respond to an ash-induced stress by producing more flowers (bean) or by bolting (lettuce). Sixth, reduction in crop yields due to ash fall only partially explains economic loss to farmers. Carrot roots exposed to 40 kg m^{-2} of ash, became soft after exposure to ash. A such textural change will certainly alter the quality of the product and thus, its sellability on the market. Last, our work has provided information about ash interception and its residence time on vegetation surface, highlighting plant-specific variables such as LAI, LAD and stem elasticity.

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Appendix

Appendix 1: pictures of beans spread with ash



Figure A-1. Seedling beans before (left) and after (right) ash application (20mm).



Figure A-2. Mature beans before (left) and after (right) ash application (5mm).



Figure A-3. Flowering beans after ash application (2mm) at flowering stage

Appendix 2: more information about VEI and volcanic terms

VEI	0	1	2	3	4	5	6	7	8
General Description	Non-Explosive	Small	Moderate	Moderate-Large	Large	Very Large			
Volumn of Tephra (m ³)	1x10 ⁴	1x10 ⁶	1x10 ⁷	1x10 ⁸	1x10 ⁹	1x10 ¹⁰	1x10 ¹¹	1x10 ¹²	
Cloud Column Height (km) Above crater Above sea level	<0.1	0.1-1	1-5	3-15	10-25		>25		
Qualitative Description	"Gentle,"	"Effusive"	"Explosive"		"Cataclysmic," "paroxysmal," "Severe," "violent," "terrific"		"colossal"		
Eruption Type (see fig. 7)	Hawaiian		Strombolian	Vulcanian		Plinian		Ultra-Plinian	
Duration (continuous blast)	<1 hr		1-6 hrs		6-12 hrs		>12 hrs		
Maximum explosivity	Lava flow	Phreatic		Explosion or Nuée ardente					
	Dome or mudflow								
Tropospheric Injection	Negligible	Minor	Moderate	Substantial					
Stratospheric Injection	None	None	None	Possible	Definite	Significant			
Eruptions	976	1239	3808	1083	412	168	50	6	0

Figure A-4. Range, characteristics and definitions of VEI and volcanic terms (Siebert et al. 2010).

VEI	Tephra Vol. (km ³)	Volcano	Region	Year
0	Effusive	Masaya	Nicaragua	1570
1	>0.00001	Poás	Costa Rica	1991
2	>0.001	Ruapehu	New Zealand	1971
3	>0.01	Nevado del Ruiz	Colombia	1985
4	>0.1	Pelée	West Indies	1902
5	>1	St. Helens	United States	1980
6	>10	Krakatau	Indonesia	1883
7	>100	Tambora	Indonesia	1815
8	>1000	Yellowstone	United States	Pleistocene

Figure A-5. Example of volcanoes associated with a value of VEI (Siebert et al. 2010).

Particle Size (mm)	Pyroclastic Fragments	
256	Coarse	Blocks and Bombs
	Fine	
64	Lapilli	
2		
.063	Coarse	Tephra or Ash
	Fine	
.004		

Figure A-6. Definition of volcanic products in function of the particle size (Blong 1984).

Appendix 3: R code

Here is a typical R script used to generate cabbage graphics with Tukey test on it. Other crop's codes are similar to this one.

```
library(readxl)
library(ggplot2)
library(multcompView)
library(ggpubr)
#CA
rdtca <- read.csv2("CA-modif.csv")

cA.frais <- ggplot( data = rdtca, mapping = aes( x = as.factor(`CA`), y = `poids.frais.tot`)) +
  geom_boxplot(aes(group = CA)) +
  labs ( y = "Fresh weight (g)", x = "Ash load (kg/m2)") +
  theme_bw() +
  theme(legend.position="top", panel.border = element_blank(), panel.grid.major = element_blank(),
        panel.grid.minor = element_blank(), axis.line = element_line(colour = "black"))

#testtukey: mean comparison
rdtca$CA <- as.factor(rdtca$CA)
model <- lm (rdtca$`poids.frais.tot` ~ rdtca$CA)
ANOVA=aov(model)
TUKEY <- TukeyHSD(x=ANOVA,'rdtca$CA', conf.level=0.95)
# I need to group the treatments that are not different each other together.
generate_label_df <- function(TUKEY, variable){
  # Extract labels and factor levels from Tukey post-hoc
```

```

Tukey.levels <- TUKEY[[variable]][,4]
Tukey.labels <- data.frame(multcompLetters(Tukey.levels)['Letters'])
#I need to put the labels in the same order as in the boxplot :
Tukey.labels$treatment=rownames(Tukey.labels)
Tukey.labels=Tukey.labels[order(Tukey.labels$treatment) , ]
return(Tukey.labels)
}
# Apply the function on my dataset
LABELS <- generate_label_df(TUKEY , "rdtca$CA")
my_colors <- c(
  rgb(143,199,74,maxColorValue = 255),
  rgb(242,104,34,maxColorValue = 255),
  rgb(111,145,202,maxColorValue = 255)
)
# Draw the basic boxplot
ca=1
a=2
b=3
fca.t <- boxplot(rdtca$poids.frais.tot~ rdtca$CA, data=rdtca$CA, ylim=c(0,600),
  par(mgp=c(b, a , 0)), xlab = "Ash load (kg/m2)", ylab = "Fresh weight (g)", cex.axis=ca)
#over <- 0.02*max( a$stats[nrow(a$stats),] )
#text( c(1:nlevels(rdtla$LA)) , a$stats[nrow(a$stats),]+over ,
# LABELS[,1] , col=my_colors[as.numeric(LABELS[,1])] )

```

Appendix 4: Raw data collected

4.1. Lettuce spread with 0 (LOA), 5 (L1A), 10 (L2A) and 20 (L3A) kg m⁻² of ash at seedling stage

	Poids frais	poids frais - sac	poids sec	Poids sec - sac	sac microperf (g)	taille (sol- apex)- cm
1 LOA	216.66	211.79	15.46	10.59	4.87	16.00
2 LOA	144.32	139.46	11.74	6.88	4.86	17.00
3 LOA	152.21	147.21	12.24	7.24	5.00	18.00
4 LOA	200.29	195.44	14.24	9.39	4.85	16.00
5 LOA	120.33	115.42	10.71	5.80	4.91	22.00
6 LOA	136.21	131.35	11.75	6.89	4.86	21.00
7 LOA	164.59	159.69	12.29	7.39	4.90	20.00
8 LOA	179.16	174.24	13.78	8.86	4.92	22.00
9 LOA	84.54	79.63	8.75	3.84	4.91	22.00
10 LOA	97.03	92.18	10.46	5.61	4.85	20.5
11 LOA	144.63	139.80	12.32	7.49	4.83	26.00

12	L0A	139.24	134.39	12.57	7.72	4.85	17.00
13	L0A	104.40	99.62	9.84	5.06	4.78	20.00
14	L0A	169.01	164.21	12.98	8.18	4.80	28.00
15	L0A	201.71	196.95	13.76	9.00	4.76	22.00
16	L0A	203.08	198.23	14.09	9.24	4.85	24.00
17	L0A	161.69	156.85	13.32	8.48	4.84	27.00
18	L0A	62.48	57.67	7.63	2.82	4.81	17.00
19	L0A	148.21	143.41	11.58	6.78	4.80	14.00
20	L0A	301.66	296.84	19.09	14.27	4.82	19.00
21	L0A	157.61	152.75	12.44	7.58	4.86	20.00
22	L0A	165.35	160.42	12.25	7.32	4.93	19.00
23	L0A	158.51	153.64	12.22	7.35	4.87	18.00
24	L0A	128.15	123.23	11.23	6.31	4.92	15.00
25	L0A	209.12	204.29	14.71	9.88	4.83	14.00
26	L0A	185.11	180.31	14.64	9.84	4.80	18.00
27	L0A	94.34	89.55	8.98	4.19	4.79	25.00
28	L0A	150.64	145.79	12.28	7.43	4.85	20.00
29	L0A	170.13	165.25	12.45	7.57	4.88	14.00
30	L0A	156.23	151.40	12.78	7.95	4.83	21.00
Moyenne L0A			152.03		7.57		19.07
1	L1A	169.86	165.01	15.14	10.29	4.85	24.00
2	L1A	154.02	149.17	13.41	8.56	4.85	25.00
3	L1A	157.49	152.66	13.27	8.44	4.83	24.00
4	L1A	97.37	92.57	9.91	5.11	4.80	24.00
5	L1A	135.98	131.17	12.28	7.47	4.81	27.00
6	L1A	156.15	151.35	12.56	7.76	4.80	28.00
7	L1A	/	0.00	0	0.00	4.74	0.00
8	L1A	151.46	146.66	11.94	7.14	4.80	25.00
9	L1A	/	0.00	0	0.00	4.76	0.00
10	L1A	/	0.00	0	0.00	4.84	0.00
11	L1A	121.03	116.15	11.2	6.32	4.88	30.00
12	L1A	151.25	146.44	12.24	7.43	4.81	39.00
13	L1A		0.00	0	0.00	4.84	0.00
14	L1A	143.21	138.36	11.86	7.01	4.85	27.00
15	L1A	135.66	130.80	11.16	6.30	4.86	35.00
16	L1A	159.46	154.62	15.44	10.60	4.84	10.00
17	L1A	196.17	191.39	16.17	11.39	4.78	21.00
18	L1A	212.17	207.37	15.55	10.75	4.80	30.00
19	L1A	157.38	152.53	12.05	7.20	4.85	32.00
20	L1A	255.73	250.92	17.32	12.51	4.81	23.00

21	L1A	149.68	144.89	12.44	7.65	4.79	22.00
22	L1A	169.62	164.86	13.74	8.98	4.76	26.00
23	L1A	157.29	152.56	12.94	8.21	4.73	26.00
24	L1A	120.73	115.99	10.15	5.41	4.74	28.00
25	L1A	207.63	202.88	14.75	10.00	4.75	32.00
26	L1A	224.74	219.98	15.07	10.31	4.76	28.00
27	L1A	135.58	130.80	11.25	6.47	4.78	33.00
28	L1A	166.27	161.51	13.6	8.84	4.76	30.00
29	L1A	180.63	175.90	13.81	9.08	4.73	33.00
30	L1A	186.69	181.96	16.18	11.45	4.73	23.00
Moyenne L1A			137.62		7.36		23.50
1	L2A	237.88	233.03	15.91	11.06	4.85	22.00
2	L2A	217.04	212.15	18.09	13.20	4.89	32.00
3	L2A	193.14	188.30	13.52	8.68	4.84	22.00
4	L2A	120.96	116.08	10.8	5.92	4.88	25.00
5	L2A	188.10	183.28	14.11	9.29	4.82	30.00
6	L2A	76.12	71.39	8.88	4.15	4.73	28.00
7	L2A	116.91	112.09	11.06	6.24	4.82	20.00
8	L2A	146.85	142.02	13.54	8.71	4.83	29.00
9	L2A	117.37	112.55	10.17	5.35	4.82	28.00
10	L2A	120.79	115.94	10.58	5.73	4.85	30.00
11	L2A	107.47	102.70	10.16	5.39	4.77	28.00
12	L2A	135.91	131.08	10.68	5.85	4.83	23.00
13	L2A	103.27	98.48	9.72	4.93	4.79	35.00
14	L2A	144.32	139.51	11.73	6.92	4.81	31.00
15	L2A	24.44	19.58	6.08	1.22	4.86	27.00
16	L2A	230.81	225.99	17.97	13.15	4.82	21.00
17	L2A	112.02	107.18	10.24	5.40	4.84	26.00
18	L2A	144.01	139.23	12	7.22	4.78	22.00
19	L2A	185.97	181.18	13.77	8.98	4.79	23.00
20	L2A	143.11	138.31	12.53	7.73	4.80	19.00
21	L2A	138.12	133.30	12.81	7.99	4.82	17.00
22	L2A	/	0.00	0	0.00	4.81	0.00
23	L2A	166.73	161.86	14.1	9.23	4.87	21.00
24	L2A	103.78	99.01	10.15	5.38	4.77	22.00
25	L2A	147.97	143.16	11.88	7.07	4.81	26.00
26	L2A	125.63	120.83	11.22	6.42	4.80	30.00
27	L2A	153.06	148.22	11.37	6.53	4.84	39.00
28	L2A	168.59	163.75	12.13	7.29	4.84	36.00
29	L2A	182.45	177.60	12.92	8.07	4.85	32.00

30	L2A	144.96	140.14	11.34	6.52	4.82	36.00
	Moyenne L2A		135.26		6.99		26.00
1	L3A	183.69	178.84	14.09	9.24	4.85	19.00
2	L3A	99.97	95.10	9.65	4.78	4.87	19.00
3	L3A	165.80	160.92	14.33	9.45	4.88	16.00
4	L3A	100.38	95.49	10.48	5.59	4.89	14.00
5	L3A	108.56	103.73	11.66	6.83	4.83	16.00
6	L3A	152.23	147.31	12.93	8.01	4.92	33.00
7	L3A	204.33	199.54	14.14	9.35	4.79	32.00
8	L3A	125.41	120.56	10.44	5.59	4.85	23.00
9	L3A	/	0.00	0	0.00	4.85	0.00
10	L3A	87.09	82.25	8.65	3.81	4.84	20.00
11	L3A	133.82	128.99	12.11	7.28	4.83	29.00
12	L3A	/	0.00	0	0.00	4.81	0.00
13	L3A	92.25	87.42	9.15	4.32	4.83	29.00
14	L3A	101.78	96.91	9.7	4.83	4.87	32.00
15	L3A	118.83	113.95	10.69	5.81	4.88	21.00
16	L3A	99.82	94.97	12.69	7.84	4.85	13.00
17	L3A	134.49	129.58	12.66	7.75	4.91	14.00
18	L3A	124.01	119.25	13.6	8.84	4.76	13.00
19	L3A	83.31	78.38	10.02	5.09	4.93	15.00
20	L3A	85.91	81.02	11.38	6.49	4.89	13.00
21	L3A	189.59	184.70	15.22	10.33	4.89	20.00
22	L3A	/	0.00	0	0.00	4.86	0.00
23	L3A	89.69	84.82	11	6.13	4.87	23.00
24	L3A	92.80	87.95	15.59	10.74	4.85	22.00
25	L3A	94.35	89.52	10.62	5.79	4.83	23.00
26	L3A	39.16	34.34	7.08	2.26	4.82	23.00
27	L3A	139.42	134.60	13.07	8.25	4.82	25.00
28	L3A	160.43	155.59	13.48	8.64	4.84	19.00
29	L3A	135.25	130.37	11.16	6.28	4.88	19.00
30	L3A	44.58	39.66	6.95	2.03	4.92	22.00
	Moyenne L3A		101.86		6.05		18.90

4.2. Lettuce spread with 0 (L0B), 5 (L1B), 10 (L2B) and 30 (L3B) kg m⁻² of ash at mature stage

Poids frais	Poids frais-sac	poids sec	poids sec-sac	sac microperf (g)	taille (sol-
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						apex)- cm
1	L0B	116.74	111.87	11.5	6.63 4.87	19.00
2	L0B	88.83	83.97	9.73	4.87 4.86	16.00
3	L0B	37.24	32.25	7.6	2.61 4.99	11.00
4	L0B	145.78	140.93	12.48	7.63 4.85	18.00
5	L0B	112.95	108.04	10.73	5.82 4.91	12.00
6	L0B	114.31	109.48	10.52	5.69 4.83	13.00
7	L0B	215.73	210.81	14.99	10.07 4.92	15.00
8	L0B	198.24	193.32	13.64	8.72 4.92	18.00
9	L0B	223.85	218.94	15.34	10.43 4.91	16.00
10	L0B	129.85	124.99	11.25	6.39 4.86	15.00
11	L0B	120.73	115.85	10.46	5.58 4.88	16.00
12	L0B	210.20	205.35	15.9	11.05 4.85	15.00
13	L0B	98.02	93.24	9.95	5.17 4.78	17.00
14	L0B	141.28	136.40	11.68	6.80 4.88	15.00
15	L0B	193.34	188.57	13.44	8.67 4.77	20.00
16	L0B	184.72	179.87	16.31	11.46 4.85	15.00
17	L0B	106.37	101.53	11.14	6.30 4.84	17.00
18	L0B	87.18	82.37	10.29	5.48 4.81	13.00
19	L0B	88.55	83.75	10.28	5.48 4.80	16.00
20	L0B	109.55	104.73	11.01	6.19 4.82	16.00
21	L0B	131.45	126.59	13.02	8.16 4.86	16.00
22	L0B	146.61	141.68	12.88	7.95 4.93	16.00
23	L0B	62.38	57.57	8.73	3.92 4.81	16.00
24	L0B	140.67	135.75	12.62	7.70 4.92	15.00
25	L0B	62.03	57.20	8.3	3.47 4.83	14.00
26	L0B	82.89	78.10	9.64	4.85 4.79	16.00
27	L0B	171.96	167.16	13.25	8.45 4.80	22.00
28	L0B	224.06	219.21	14.95	10.10 4.85	21.00
29	L0B	105.32	100.52	9.64	4.84 4.80	18.00
30	L0B	141.25	136.42	11.48	6.65 4.83	22.00
	Moyenne L0B		128.22		6.90	16.30
1	L1B	229.29	224.43	24.78	19.92 4.86	21.00
2	L1B	176.93	172.07	18.41	13.55 4.86	19.00
3	L1B	99.21	94.34	13.02	8.15 4.87	19.00
4	L1B	112.63	107.78	12.99	8.14 4.85	19.00
5	L1B	135.02	130.03	14.67	9.68 4.99	20.00
6	L1B	94.44	89.63	13.77	8.96 4.81	19.00
7	L1B	145.42	140.51	14.47	9.56 4.91	24.00

8	L1B	114.48	109.50	13.06	8.08	4.98	24.00
9	L1B	109.99	105.08	11.73	6.82	4.91	18.00
10	L1B	147.24	142.36	13.33	8.45	4.88	23.00
11	L1B	157.60	152.76	13.46	8.62	4.84	23.00
12	L1B	145.14	140.28	14.93	10.07	4.86	19.00
13	L1B	67.80	63.01	9.13	4.34	4.79	16.00
14	L1B	105.27	100.46	10.84	6.03	4.81	18.00
15	L1B	178.62	173.80	15.04	10.22	4.82	14.00
16	L1B	160.00	155.15	24.59	19.74	4.85	24.00
17	L1B	135.79	130.95	14.21	9.37	4.84	24.00
18	L1B	51.74	46.85	8.8	3.91	4.89	20.00
19	L1B	138.61	133.81	19.03	14.23	4.80	23.00
20	L1B	/	0.00	0	0.00	/	0.00
21	L1B	79.35	74.46	10.76	5.87	4.89	16.00
22	L1B	66.66	61.75	11.1	6.19	4.91	21.00
23	L1B	51.44	46.68	8.78	4.02	4.76	14.00
24	L1B	123.76	118.83	13.66	8.73	4.93	13.00
25	L1B	/	0.00	0	0.00	/	10.00
26	L1B	82.74	77.96	11.84	7.06	4.78	11.00
27	L1B	/	0.00	0	0.00	/	8.00
28	L1B	38.81	33.95	7.07	2.21	4.86	12.00
29	L1B	41.25	36.44	7.84	3.03	4.81	13.00
30	L1B	63.58	58.76	8.59	3.77	4.82	11.00
Moyenne L1B			97.39		7.62		17.20
1	L2B	163.55	158.68	14.7	9.83	4.87	25.00
2	L2B	174.60	169.74	15.7	10.84	4.86	21.00
3	L2B	106.60	101.67	11.52	6.59	4.93	20.00
4	L2B	32.52	27.58	8.66	3.72	4.94	12.00
5	L2B	35.16	30.40	9.34	4.58	4.76	11.00
6	L2B	78.18	73.36	10.27	5.45	4.82	14.00
7	L2B	95.50	90.56	11.66	6.72	4.94	16.00
8	L2B	54.35	49.44	9.03	4.12	4.91	16.00
9	L2B	93.73	88.82	10.17	5.26	4.91	17.00
10	L2B	49.32	44.45	8.54	3.67	4.87	18.00
11	L2B	95.53	90.65	11	6.12	4.88	21.00
12	L2B	59.93	55.08	9.04	4.19	4.85	16.00
13	L2B	20.97	16.21	6.56	1.80	4.76	13.00
14	L2B	82.49	77.70	10.02	5.23	4.79	15.00
15	L2B	86.02	81.13	10.08	5.19	4.89	12.00

16	L2B	181.16	176.31	17.03	12.18	4.85	17.00
17	L2B	/	0.00	0	0.00	/	/
18	L2B	25.25	20.44	7.14	2.33	4.81	15.00
19	L2B	46.76	41.94	8.52	3.70	4.82	15.00
20	L2B	81.86	77.05	10.16	5.35	4.81	15.00
21	L2B	83.92	79.06	10.19	5.33	4.86	16.00
22	L2B	58.41	53.52	9.49	4.60	4.89	17.00
23	L2B	/	0.00	0	0.00	/	/
24	L2B	/	0.00	0	0.00	/	/
25	L2B	110.74	105.91	14.31	9.48	4.83	19.00
26	L2B	54.46	49.67	8.47	3.68	4.79	16.00
27	L2B	/	0.00	0	0.00	/	/
28	L2B	/	0.00	0	0.00	/	/
29	L2B	86.92	82.12	11.03	6.23	4.80	16.00
30	L2B	87.56	82.71	9.74	4.89	4.85	15.00
	Moyenne L2B		64.14		4.70		13.60
1	L3B	96.43	91.52	11.33	6.42	4.91	20.00
2	L3B	106.03	101.29	11.2	6.46	4.74	20.00
3	L3B	99.31	94.34	11.9	6.93	4.97	18.00
4	L3B	/	0.00	0	0.00	/	0.00
5	L3B	77.54	72.61	12.15	7.22	4.93	14.00
6	L3B	84.15	79.29	12.32	7.46	4.86	18.00
7	L3B	19.74	14.84	6.79	1.89	4.90	9.00
8	L3B	69.75	64.86	10.04	5.15	4.89	12.00
9	L3B	37.79	32.89	7.84	2.94	4.90	17.00
10	L3B	/	0.00	0	0.00	/	0.00
11	L3B	110.32	105.48	13.68	8.84	4.84	19.00
12	L3B	60.14	55.29	11.62	6.77	4.85	18.00
13	L3B	39.89	35.10	9.78	4.99	4.79	14.00
14	L3B	53.45	48.57	8.34	3.46	4.88	17.00
15	L3B	164.95	160.13	15.38	10.56	4.82	22.00
16	L3B	/	0.00	0	0.00	/	0.00
17	L3B	/	0.00	0	0.00	/	0.00
18	L3B	/	0.00	0	0.00	/	0.00
19	L3B	28.54	23.73	6.9	2.09	4.81	21.00
20	L3B	/	0.00	0	0.00	/	0.00
21	L3B	/	0.00	0	0.00	/	0.00
22	L3B	/	0.00	0	0.00	/	0.00
23	L3B	/	0.00	0	0.00	/	0.00

24	L3B	40.14	35.23	7.99	3.08	4.91	14.00
25	L3B	57.27	52.44	8.94	4.11	4.83	20.00
26	L3B	/	0.00	0	0.00	/	0.00
27	L3B	143.66	138.84	14.97	10.15	4.82	23.00
28	L3B	16.63	11.80	6.14	1.31	4.83	13.00
29	L3B	77.28	72.48	11.14	6.34	4.80	17.00
30	L3B	/	0.00	0	0.00	/	0.00
	Moyenne L3B		43.02		3.54		10.87

4.3. Cabbage spread with 0 (C0B), 5 (C1B), 10 (C2B) and 30 (C3B) kg m⁻² of ash at mature stage

		Poi ds frai s cor ps	poi ds frai s têt e	poi ds frai s têt e	poi ds frai s têt e	poid s sac cor ps	poid s sac tete	poi ds sec cor ps	Poi ds sec têt e	poi ds sec cor ps	poi ds sec têt e	Dia me tre têt e	taille tet e	Dia m cor ps	app rox vol um e
C0B	1	270	160	265	155	5	4.84	36	23	31	18	26	20	52	1 520
C0B	2	296	229	291	224	5	4.81	27	23	22	18	24	19	54	1 456
C0B	3	324	279	319	274	5	4.80	30	27	25	22	18	18	53	1 324
C0B	4	353	72	348	67	5	4.82	35	12	30	7	14	10	47	1 140
C0B	5	222	71	217	66	5	4.86	22	11	17	6	19	14	45	1 266
C0B	6	235	118	230	113	5	4.93	38	15	33	10	19	16	45	1 304
C0B	7	282	32	277	28	5	4.81	27	8	22	3	12	10	48	1 120
C0B	8	319	79	314	74	5	4.92	39	14	34	9	15	14	53	1 210
C0B	9	264	45	259	40	5	4.83	29	10	24	5	13	8	55	2 104
C0B	10	301	74	296	69	5	5	32	14	27	9	16	14	59	1 224
C0B	11	323	124	318	119	5	4.80	39	18	34	13	21	17	57	1 357
C0B	12	406	31	401	26	5	4.85	36	8	31	3	21	9	51	2 189
C0B	13	267	47	262	43	5	4.80	25	9	20	5	20	8	45	3 160
C0B	14	170	90	166	85	5	4.83	21	15	16	10	12	12	43	1 144
C0B	15	351	13	346	9	5	5	32	6	27	1	4	7	49	1 28
				287	93					26	9	17	13	50	1 221
C1B	1	293	31	288	27	4.86	4.84	47	8	42	4	14	7	52	2 98
C1B	2	356	31	351	26	4.86	4.89	44	8	39	3	16	10	53	2 160
C1B	3	276	37	271	33	4.87	4.80	37	9	32	4	9	11	50	1 99
C1B	4	421	50	416	45	4.85	5	49	9	44	5	8	7	47	1 56
C1B	5	522	50	517	45	4.99	4.89	59	9	54	4	7	9	58	1 63

C1B	6	173	17	168	12	4.81	4.91	22	6	17	2	16	7	40	2	112
C1B	7	357	25	352	20	4.91	4.76	35	7	30	2	14	6	41	2	84
C1B	8	247	16	242	11	4.98	4.93	26	6	21	1	14	4	35	4	56
C1B	9	287	19	282	14	4.91	5	34	7	29	2	11	4	35	3	44
C1B	10	469	20	465	15	4.88	4.78	58	7	53	2	18	10	43	2	180
C1B	11	285	19	280	14	4.84	5	39	7	34	2	13	10	41	1	130
C1B	12	429	26	424	21	4.86	4.86	41	8	36	3	14	8	43	2	112
C1B	13	510	58	505	53	4.79	4.81	56	10	51	5	9	10	50	1	90
C1B	14	264	117	259	112	4.81	4.82	31	17	26	12	10	12	54	1	120
C1B	15	356	38	351	33	4.82	5	33	8	28	3	13	4	37	3	52
C1B	16	267	26	262	21	4.85	5	31	7	26	3	15	8	46	2	120
				340	31					35	4	13	8	45	2	100
C2B	1	261	45	256	40	4.87	5	36	11	31	6	16	10	48	2	160
C2B	2	232	37	227	32	4.86	4.81	32	9	27	4	10	9	37	1	90
C2B	3	268	44	263	39	4.93	4.82	49	9	44	4	7	8	38	1	56
C2B	4	280	59	275	54	4.94	4.81	41	10	36	6	5	14	49	0	70
C2B	5	349	27	345	22	4.76	4.86	35	7	30	3	12	9	42	1	108
C2B	6	270	30	265	25	4.82	4.89	34	8	29	3	7	5	40	1	35
C2B	7	411	51	406	46	4.94	5	62	14	57	9	12	12	52	1	144
C2B	8	289	21	284	16	4.91	5	31	7	26	2	10	9	44	1	90
C2B	9	319	22	314	18	4.91	4.83	36	7	31	2	12	7	40	2	84
C2B	10	0	/	/		0	0	0	0	0	0	0	0	0	0	0
C2B	11	266	18	261	13	4.88	4.79	31	7	26	2	13	3	39	4	39
C2B	12	374	24	369	19	4.85	5	45	7	40	2	7	13	51	1	91
C2B	13	488	31	484	26	4.76	4.80	51	8	46	3	8	8	53	1	64
C2B	14	460	29	455	24	4.79	4.85	57	8	52	3	15	12	51	1	180
C2B	15	243	32	238	27	4.89	5	27	8	22	3	10	5	35	2	50
C2B	16	276	20	271	15	4.85	5	28	7	23	2	8	3	36	3	24
				314	28					33	3	10	8	41	1	75
C3B	1	309	62	304	57	4.91	5	31	11	26	6	12	10	41	1	120
C3B	2	289	29	284	24	4.74	5	36	8	32	3	12	8	49	2	96
C3B	3	240	22	235	17	4.97	4.81	40	7	35	2	11	9	42	1	99
C3B	4	241	17	236	13	4.92	5	26	6	21	2	5	3	37	2	15
C3B	5	364	63	359	58	4.93	5	45	10	41	5	6	9	44	1	54
C3B	6	353	32	348	27	4.86	5	43	8	38	3	11	10	43	1	110
C3B	7	315	24	310	19	4.90	5	31	7	26	2	11	7	42	2	77
C3B	8	263	30	259	25	4.89	4.91	39	8	34	3	13	9	44	1	117
C3B	9	140	31	135	26	4.90	4.83	19	8	14	4	15	7	34	2	105
C3B	10	178	36	173	31	5	5	25	9	21	4	11	8	31	1	88
C3B	11	289	40	285	35	4.84	4.82	53	10	48	5	11	7	40	2	77

C3B	12	326	25	321	20	4.85	4.83	40	7	36	2	10	5	39	2	50
C3B	13	0	0	/	/	0	0	0	0	0	0	0	0	0	0	0
C3B	14	343	66	338	61	4.88	5	47	11	42	6	11	8	47	1	88
C3B	15	176	20	171	15	4.82	5	20	7	15	2	13	8	40	2	104
C3B	16	239	21	234	16	4.87	5	27	7	22	2	14	9	38	2	126
				266	30					28	3	10	7	38	1	76

4.4. Cabbage spread with 0 (C0A), 5 (C1A), 10 (C2A) and 20 (C3A) kg m⁻² of ash at seedling stage

		Poi ds frai s cor ps	poi ds frai s têt e	poi ds frai s ps- sac	poi ds frai s e- sac	poid s sac corp s	poi ds sac tete	Poi ds sec cor ps	Poi ds sec têt e	poi ds sec cor ps- sac	Poi ds sec têt e- sac	Dia me tre tet e	dia m env erg ure	Dia m/t aill e têt e	vol	
COA	1	266	70	261	65	5	4.84	35	14	31	9	15	14	47	1	210
COA	2	258	207	253	202	5	4.81	28	28	23	23	31	18	53	2	558
COA	3	282	140	277	136	5.00	4.80	27	20	22	15	23	14	53	2	322
COA	4	419	40	414	35	4.85	4.82	33	9	28	4	18	11	43	2	198
COA	5	497	95	492	90	4.91	4.86	46	14	41	9	6	13	59	0	78
COA	6	365	140	360	135	4.86	4.93	33	18	28	13	22	17	55	1	374
COA	7	246	203	241	198	4.90	4.87	22	21	17	16	26	20	49	1	520
COA	8	351	83	346	78	4.92	4.92	33	14	28	9	18	17	53	1	306
COA	9	278	11	273	6	4.91	4.83	34	6	29	1	7	5	45	1	35
COA	10	368	46	363	41	4.85	4.80	35	10	31	5	19	10	50	2	190
COA	11	273	146	268	142	4.83	4.79	27	22	23	17	20	19	63	1	380
COA	12	229	160	224	155	4.85	4.85	20	19	15	14	22	14	55	2	308
COA	13	382	135	377	130	4.78	4.88	32	17	27	12	24	11	57	2	264
COA	14	341	116	336	111	4.80	4.83	31	17	26	12	18	15	55	1	270
COA	15	233	9	228	4	4.76	5	22	6	17	1	4	6	44	1	24
COA	16	288	108	283	103	4.85	5	27	16	22	11	17	17	53	1	289
				312	102					25	11	18	14	52	1	250
C1A	1	246	51	241	46	4.85	4.78	25	11	21	6	16	12	47	1	192
C1A	2	219	14	214	10	4.85	4.80	24	6	19	2	16	7	51	2	112
C1A	3	210	62	205	57	4.83	4.85	27	15	22	11	13	19	58	1	247
C1A	4	345	35	340	31	4.80	4.81	37	8	32	3	12	11	56	1	132
C1A	5	218	22	214	17	4.81	4.79	26	7	21	2	12	7	40	2	84
C1A	6	242	80	237	75	4.80	4.76	28	13	23	8	14	13	57	1	182
C1A	7	261	17	257	12	4.74	4.73	28	7	23	2	11	8	55	1	88

C1A	8	235	51	230	46	4.80	4.74	27	11	22	6	11	10	49	1	110
C1A	9	204	19	200	14	4.76	4.75	29	7	24	3	9	3	39	3	27
C1A	10	182	51	177	46	4.84	4.76	27	12	22	7	11	10	48	1	110
C1A	11	228	41	223	37	4.88	4.78	29	10	24	5	10	9	48	1	90
C1A	12	317	61	312	56	4.81	4.76	40	14	35	9	11	12	52	1	132
C1A	13	241	24	236	19	4.84	4.73	30	7	25	2	10	9	43	1	90
C1A	14	248	50	243	46	4.85	4.73	27	10	22	5	12	12	52	1	144
C1A	15	350	23	345	18	4.86	5	39	8	34	3	11	10	52	1	110
C1A	16	149	18	144	13	4.84	5	20	7	16	2	9	10	31	1	90
			239	34						24	5	12	10	49	1	119
C2A	1	211	0	206	0	4.85	0	26	0	21	0	0	0	39	0	0
C2A	2	202	36	197	31	4.89	4.78	25	9	20	4	14	11	46	1	154
C2A	3	150	38	145	33	4.84	4.79	22	9	17	4	17	9	43	2	153
C2A	4	275	53	270	49	4.88	4.80	28	10	23	5	16	10	48	2	160
C2A	5	182	0	177	0	4.82	0	24	0	20	0	0	0	43	0	0
C2A	6	172	36	167	32	4.73	4.81	21	9	16	4	10	7	44	1	70
C2A	7	217	12	212	7	4.82	4.87	30	7	25	2	14	9	43	2	126
C2A	8	129	42	124	38	4.83	4.77	25	11	20	6	11	8	41	1	88
C2A	9	162	0	157	0	4.82	0	23	0	18	0	0	0	36	0	0
C2A	10	218	36	213	31	4.85	4.80	30	9	25	4	16	12	49	1	192
C2A	11	267	45	263	40	4.77	4.84	31	10	26	5	17	10	46	2	170
C2A	12	292	65	287	60	4.83	4.84	38	11	33	7	14	9	55	2	126
C2A	13	148	45	143	40	4.79	4.85	23	10	18	5	13	8	33	2	104
C2A	14	217	64	212	59	4.81	4.82	24	12	20	7	15	9	41	2	135
C2A	15	186	27	181	22	4.86	5	24	8	19	3	14	7	42	2	98
C2A	16	160	29	155	24	4.82	5	22	10	18	5	10	5	42	2	50
			194	29						21	4	11	7	43	1	81
C3A	1	246	0	241	0	4.85	0	26	0	21	0	0	0	37	0	0
																#V
																ALE
C3A	2	/	/	/	/	0	0	0	0	/	/	/	/	/	/	UR!
C3A	3	149	37	144	32	4.88	4.93	20	9	15	4	10	7	34	1	70
C3A	4	191	40	186	35	4.89	4.89	27	10	22	5	16	12	38	1	192
C3A	5	126	0	121	0	4.83	0	22	0	17	0	0	0	34	0	0
C3A	6	180	0	176	0	4.92	0	22	0	18	0	0	0	41	0	0
C3A	7	177	0	172	0	4.79	0	23	0	18	0	0	0	39	0	0
C3A	8	129	0	124	0	4.85	0	17	0	12	0	0	0	30	0	0
C3A	9	208	0	203	0	4.85	0	25	0	20	0	0	0	42	0	0
C3A	10	150	30	145	25	4.84	4.82	24	8	19	4	11	9	36	1	99
C3A	11	175	0	170	0	4.83	0	27	0	22	0	0	0	41	0	0

C3A	12	164	36	159	31	4.81	4.84	25	8	20	4	12	10	40	1	120
C3A	13	142	0	138	0	4.83	0	20	0	16	0	0	0	32	0	0
C3A	14	221	21	216	16	4.87	4.92	28	8	24	3	14	8	44	2	112
C3A	15	191	28	186	23	4.88	5	26	9	21	4	13	8	43	2	104
C3A	16	218	24	213	19	4.85	5	29	8	24	3	11	11	43	1	121
				173	12					19	2	6	4	38	1	25

4.5. Beans spread with 0 (FC0), 2 (FC2), 5 (FC5) and 10 (FC10) kg m⁻² of ash at flowering stage

FC (kg m-2)	poids frais	poids frais-sac	poids sac	gousse frais	gousse frais-sac	poids sec	poids sec-sac	gousse sec	gousse sec-sac	tot frais	tot sec
2	36	32	5			11	6			32	6
2	18	14	5			8	3			14	3
2	20	16	5			9	4			16	4
2	51	46	5			14	9			46	9
2	37	32	5			15	10			32	10
2	35	31	5			12	7			31	7
2	56	52	5			16	12			52	12
2	39	34	5			12	7			34	7
2	41	36	5			13	8			36	8
2	27	22	5			10	6			22	6
2	20	16	5			10	5			16	5
2	25	20	5			11	7			20	7
2	30	25	5			12	7			25	7
2	34	29	5			14	9			29	9
2	31	26	5	44	39	11	7	13	9	65	15
2	49	44	5			15	10			44	10
2	41	36	5	19	15	13	8	7	3	51	11
2	18	14	5			8	4			14	4
2	35	30	5	27	22	11	7	10	5	53	12
2	40	35	5			13	9			35	9
2	25	20	5			12	7			20	7
2	39	35	5			13	9			35	9
2	22	17	5	17	12	10	6	7	2	29	8
5	29	24	5	22	18	11	6	8	4	42	10
5	38	34	5			14	9			34	9
5	31	26	5			12	7			26	7
5	38	34	5			12	7			34	7
5	31	26	5			11	7			26	7
5	22	17	5			12	7			17	7

5	57	52	5			16	12			52	12
5	27	23	5			12	7			23	7
5	21	16	5	16	11	9	5	6	2	28	6
5	22	17	5			9	5			17	5
5	30	25	5			10	6			25	6
5	21	16	5			9	4			16	4
5	19	14	5			9	4			14	4
5	24	19	5			11	6			19	6
5	15	10	5			9	5			10	5
5	23	19	5			10	6			19	6
5	31	27	5			12	7			27	7
5	36	31	5			13	9			31	9
5	18	13	5			9	4			13	4
5	23	18	5			9	5			18	5
5	30	25	5	18	14	11	6	8	3	39	9
5	39	35	5			12	8			35	8
5	30	25	5			12	7			25	7
10	10	5	5			7	3			5	3
10	15	10	5			10	5			10	5
10	6	2	5			6	1			2	1
10	18	13	5			8	4			13	4
10	20	16	5			7	3			16	3
10	29	24	5			9	5			24	5
10	36	31	5			10	6			31	6
10	29	24	5			9	5			24	5
10	30	25	5			10	5			25	5
10	9	4	5			6	2			4	2
10	12	7	5			7	2			7	2
10	9	4	5			6	1			4	1
10	26	21	5			10	5			21	5
10	21	16	5			9	4			16	4
10	19	14	5			8	4			14	4
10	28	23	5	18	14	10	5	8	3	37	8
10	30	25	5			10	6			25	6
10	28	24	5			12	7			24	7
10	53	48	5	18	14	18	13	7	3	62	16
10	21	17	5	14	9	9	4	7	2	26	7
10	25	21	5			10	5			21	5
10	23	19	5			8	4			19	4
10	35	30	5			12	8			30	8
0	22	17	5			9	4			17	4
0	16	11	5			7	2			11	2
0	21	16	5			8	4			16	4

0	39	34	5			13	8			34	8
0	36	31	5			10	6			31	6
0	29	25	5	20	15	10	5	8	3	40	8
0	40	35	5			11	7			35	7
0	32	27	5			10	6			27	6
0	34	29	5	16	11	10	6	7	2	40	8
0	24	20	5			11	7			20	7
0	11	7	5			7	3			7	3
0	29	25	5			12	7			25	7
0	18	13	5			8	3			13	3
0	18	14	5			9	4			14	4
0	45	41	5			15	10			41	10
0	34	29	5			11	7			29	7
0	23	18	5			11	6			18	6
0	37	32	5			13	9			32	9
0	53	48	5			15	10			48	10
0	33	28	5			14	10			28	10
0	34	29	5	15	10	11	6	7	2	39	8

4.6. Beans spread with 0 (FD0), 5 (FD5), 10 (FD10) and 30 (FD30) kg m⁻² of ash at fruiting stage

FD	poids		poids sac	gousse		poids sec	poids sec-sac	gousse sec	gousse sec-sac	tot frais	tot sec
	poids frais	frais- sac		gousse frais	frais- sac						
5	53	48	5	30	25	15	11	12	7	73	18
5	15	10	5			7	2			10	2
5	39	34	5			15	10			34	10
5	20	16	5			8	4			16	4
5	42	37	5	14	10	14	10	6	2	47	11
5	25	20	5			10	6			20	6
5	12	7	5			6	2			7	2
5	14	10	5			7	3			10	3
5	27	23	5	8	4	9	4	5	1	26	5
5	18	13	5	9	5	8	3	6	1	18	4
5	55	50	5	13	8	14	9	6	1	58	11
5	19	14	5			7	2			14	2
5	24	19	5	30	25	13	8	12	7	44	15
5	31	26	5	13	8	13	8	7	2	34	10
5	36	31	5	8	4	12	7	6	1	35	9
5	39	34	5	9	5	16	11	6	1	39	12
5	30	25	5			14	9			25	9
5	20	16	5	11	7	10	5	6	1	22	6

5	26	21	5	9	4	9	4	6	1	25	5
5	22	17	5			9	5			17	5
5	61	56	5			16	12			56	12
5	33	29	5	16	11	11	6	6	2	40	8
5	45	40	5			14	9			40	9
10	37	32	5	11	7	13	8	6	2	39	10
10	34	29	5	14	9	11	6	6	2	39	8
10	22	18	5			10	5			18	5
10	37	33	5			11	6			33	6
10	39	34	5	10	5	12	7	6	1	39	8
10	33	29	5	18	13	11	6	8	3	42	9
10	34	30	5	8	3	12	8	6	1	33	9
10	42	37	5			11	7			37	7
10	23	18	5			8	3			18	3
10	37	32	5			13	8			32	8
10	41	37	5	13	9	15	10	7	2	45	12
10	18	13	5			8	3			13	3
10	38	33	5	9	4	14	10	6	1	38	11
10	14	9	5			7	3			9	3
10	12	7	5			7	2			7	2
10	45	40	5	9	4	15	10	6	1	44	11
10	37	32	5			11	6			32	6
10	19	15	5			8	4			15	4
10	24	19	5			9	4			19	4
10	18	13	5			9	4			13	4
10	25	20	5			10	6			20	6
10	38	34	5			16	11			34	11
30	40	36	5	16	12	12	7	8	3	47	11
30	9	4	5			7	2			4	2
30	40	35	5			13	8			35	8
30	9	4	5			7	2			4	2
30	13	9	5			9	4			9	4
30	32	28	5			11	7			28	7
30	36	32	5			12	7			32	7
30	17	12	5			9	5			12	5
30	22	17	5			11	6			17	6
30	19	14	5			9	5			14	5
30	23	18	5			10	6			18	6
30	25	20	5			11	7			20	7
30	21	16	5			11	7			16	7
30	23	19	5			10	6			19	6
30	14	9	5			8	3			9	3
30	12	7	5			7	3			7	3

30	8	4	5			7	2			4	2
0	22	17	5			9	4			17	4
0	16	11	5			7	2			11	2
0	21	16	5			8	4			16	4
0	39	34	5			13	8			34	8
0	36	31	5			10	6			31	6
0	29	25	5	20	15	10	5	8	3	40	8
0	40	35	5			11	7			35	7
0	32	27	5			10	6			27	6
0	34	29	5	16	11	10	6	7	2	40	8
0	24	20	5			11	7			20	7
0	11	7	5			7	3			7	3
0	29	25	5			12	7			25	7
0	18	13	5			8	3			13	3
0	18	14	5			9	4			14	4
0	45	41	5			15	10			41	10
0	34	29	5			11	7			29	7
0	23	18	5			11	6			18	6
0	37	32	5			13	9			32	9
0	53	48	5			15	10			48	10
0	33	28	5			14	10			28	10
0	34	29	5	15	10	11	6	7	2	39	8

4.7. Carrot spread at seedling stage (CA) and mature stage (CB) with 0 (TC), 5 (CA1 and CB1), 10 (CA2), 20 (CA3 and CB2) 40 (CB3) kg m⁻² of ash

		poids		poids		poids		poids		poids		poids		
		frai	carot	frai	carot	frai	carot	frai	carot	frai	carot	frai	carot	
		ds	sec	ds	sec	ds	sec	ds	sec	ds	sec	ds	sec	
		net	net	net	net	net	net	net	net	net	net	net	net	
TC	1	35	57	5	53	31	5	93	83	10	12	6	7	13
TC	2	33	46	5	41	29	5	79	70	10	11	6	7	12
TC	3	25	67	5	62	20	5	91	82	8	13	3	8	11
TC	4	21	56	5	52	16	5	77	68	8	12	4	7	11
TC	5	21	55	5	50	16	5	75	66	7	12	3	7	10
TC	6	22	39	5	35	17	5	61	52	8	10	3	5	8
TC	7	25	51	5	47	20	5	76	67	9	12	4	8	12
TC	8	18	45	5	40	14	5	63	54	8	10	3	5	9
TC	9	29	65	5	61	24	5	94	85	9	14	4	9	14
TC	10	21	54	5	49	16	5	75	66	8	12	3	8	11
TC	11	43	74	5	69	38	5	117	107	12	17	7	12	19
TC	12	21	43	5	38	16	5	64	54	8	11	3	6	10

TC	13	31	62	5	57	26	5	93	84	10	15	5	10	15
TC	14	22	61	5	56	17	5	82	73	8	14	3	10	13
TC	15	21	54	5	49	16	5	75	65	8	12	3	7	11
TC	16	26	51	5	46	22	5	77	68	9	12	4	7	12
TC	17	33	59	5	54	28	5	92	82	10	13	5	9	14
TC	18	30	53	5	49	26	5	84	74	10	13	5	8	13
TC	19	18	30	5	25	13	5	47	38	8	9	3	4	8
TC	20	32	42	5	38	27	5	75	65	10	10	5	5	10
TC	21	23	48	5	44	18	5	71	62	9	11	4	6	10
TC	22	26	63	5	58	21	5	88	79	9	13	4	9	13
TC	23	19	20	5	16	14	5	39	30	8	8	3	3	6
TC	24	38	70	5	65	34	5	108	99	11	15	7	11	17
					48		5	0	48				7	7
CA1	1	19	32	1	31	14	5	50	45	7	5	3	4	7
CA1	2	32	59	1	59	28	5	91	86	10	9	5	8	13
CA1	3	32	33	1	33	27	5	65	60	10	6	6	6	12
CA1	4	28	31	1	31	23	5	59	54	10	6	5	5	10
CA1	5	35	42	1	41	30	5	76	71	10	7	5	6	11
CA1	6	34	45	1	44	30	5	79	74	11	8	6	7	13
CA1	7	26	47	1	47	22	5	74	69	9	8	4	8	12
CA1	8	20	53	1	52	15	5	73	68	8	8	3	7	11
CA1	9	23	54	1	54	18	5	77	72	9	9	4	8	12
CA1	10	27	53	1	52	22	5	80	75	9	9	5	9	14
CA1	11	27	56	1	55	23	5	83	78	10	10	5	9	14
CA1	12	20	25	1	25	15	5	45	40	9	4	4	4	8
CA1	13	25	29	1	29	20	5	54	49	9	5	4	4	8
CA1	14	27	44	1	44	22	5	71	66	10	8	5	7	13
CA1	15	35	37	1	37	31	5	73	68	10	5	6	5	11
CA1	16	25	50	1	49	20	5	75	69	9	8	4	7	12
CA1	17	21	64	1	64	17	5	86	80	9	8	4	7	11
CA1	18	21	46	1	45	16	5	66	61	8	7	4	6	10
CA1	19	23	45	1	44	19	5	68	63	10	9	5	8	13
CA1	20	20	32	1	31	15	5	51	46	9	5	4	5	9
CA1	21	19	46	1	45	14	5	64	59	9	7	4	7	11
CA1	22	24	58	1	57	19	5	82	77	10	10	5	10	14
CA1	23	16	66	1	66	11	5	82	77	8	11	4	10	14
CA1	24	15	16	1	15	10	5	30	25	9	3	4	3	7
				1	44	-5	5	0	39			-5	7	2
CA2	1	21	20	1	20	16	5	41	36	8	4	4	4	7
CA2	2	22	45	1	45	17	5	67	62	8	7	4	7	10
CA2	3	32	44	1	44	27	5	76	71	10	9	5	8	13
CA2	4	21	12	1	11	16	5	33	27	8	2	3	2	5
CA2	5	28	65	1	65	23	5	93	88	9	11	5	10	15

CA2	6	19	35	1	35	15	5	54	49	8	6	3	6	9
CA2	7	25	40	1	40	20	5	65	60	9	7	4	6	10
CA2	8	29	33	1	33	24	5	62	57	9	6	5	6	10
CA2	9	36	67	1	67	31	5	103	98	10	10	6	10	15
CA2	10	15	5	1	5	11	5	21	15	7	1	2	1	3
CA2	11	19	25	1	24	14	5	44	38	8	4	3	3	7
CA2	12	28	25	1	25	23	5	53	48	9	5	5	4	9
CA2	13	27	40	1	40	22	5	67	62	9	8	5	7	12
CA2	14	14	9	1	8	9	5	23	18	7	2	2	1	4
CA2	15	34	35	1	35	29	5	69	64	11	6	6	6	12
CA2	16	16	21	1	20	11	5	37	32	7	4	2	4	6
CA2	17	15	23	1	22	11	5	38	33	7	4	2	3	5
CA2	18	24	43	1	43	19	5	67	62	9	8	4	7	11
CA2	19	16	35	1	34	12	5	51	46	8	6	3	6	8
CA2	20	23	53	1	53	19	5	77	71	9	8	4	8	12
CA2	21	17	49	1	48	13	5	66	61	9	9	4	8	12
CA2	22	18	37	1	37	14	5	56	50	9	7	4	6	10
CA2	23	14	47	1	47	9	5	61	55	9	9	4	9	13
CA2	24	17	40	1	40	12	5	57	52	9	6	4	6	10
				1	35	-5	5	0	30			-5	6	1
CA3	1	26	17	1	17	22	5	44	39	10	3	5	3	8
CA3	2	15	52	1	51	11	5	67	62	7	8	3	7	10
CA3	3	28	20	1	20	24	5	48	43	9	4	5	3	8
CA3	4	17	34	1	33	12	5	50	45	8	7	3	6	9
CA3	5	31	17	1	16	26	5	47	42	10	3	6	3	8
CA3	6	25	18	1	18	20	5	43	38	9	3	4	3	7
CA3	7	25	33	1	33	21	5	59	53	9	6	4	5	10
CA3	8	21	33	1	33	16	5	54	49	8	6	4	5	9
CA3	9	30	30	1	30	25	5	60	55	9	5	4	4	9
CA3	10	26	49	1	48	22	5	75	70	9	8	5	7	12
CA3	11	19	41	1	41	14	5	60	55	8	7	3	6	9
CA3	12	30	44	1	43	26	5	74	69	10	7	5	7	12
CA3	13	21	37	1	37	16	5	58	53	9	6	4	6	10
CA3	14	14	27	1	27	9	5	41	36	7	6	3	6	8
CA3	15	25	41	1	41	20	5	66	61	10	8	5	7	12
CA3	16	21	23	1	23	16	5	44	39	8	6	4	6	10
CA3	17	19	29	1	29	14	5	48	43	9	6	4	5	9
CA3	18	17	46	1	46	12	5	63	58	8	8	3	7	11
CA3	19	13	28	1	27	8	5	40	35	8	5	3	5	8
CA3	20	21	53	1	52	16	5	74	69	9	8	4	7	11
CA3	21	22	43	1	43	17	5	65	60	9	8	5	7	12
CA3	22	8	11	1	11	4	5	19	14	7	2	2	2	4
CA3	23	21	32	1	32	16	5	53	48	9	5	5	5	9

CA3	24	19	34	1	34	14	5	53	48	9	6	5	6	10
				1	33	-5	5	0	28			-5	5	1
CB1	1	27	36	1	36	22	5	63	58	9	6	5	5	10
	2	25	45	1	44	20	5	70	64	9	7	5	7	12
	3	27	32	1	31	22	5	59	54	10	5	5	5	10
	4	28	64	1	63	23	5	91	86	10	12	5	11	16
	5	22	44	1	43	18	5	66	61	8	6	3	6	9
	6	27	34	1	34	23	5	62	57	9	7	4	6	11
	7	23	57	1	56	18	5	79	74	8	7	3	7	10
	8	22	70	1	69	17	5	92	86	8	9	3	9	12
	9	26	49	1	49	22	5	75	70	9	6	4	5	9
	10	21	28	1	28	16	5	49	44	8	5	4	4	8
	11	21	38	1	37	16	5	59	53	9	6	4	6	9
	12	27	44	1	44	22	5	71	66	9	7	4	7	11
	13	28	33	1	32	24	5	61	56	10	6	5	6	11
	14	23	56	1	55	19	5	79	74	8	9	4	8	12
	15	23	37	1	36	18	5	60	55	9	6	4	5	10
	16	22	43	1	42	18	5	65	60	9	7	4	7	11
	17	19	45	1	44	15	5	64	59	8	7	3	7	10
	18	21	56	1	55	16	5	77	72	8	9	3	8	11
	19	27	68	1	67	22	5	95	90	9	11	4	11	15
	20	14	9	1	8	9	5	23	18	7	2	2	1	3
	21	40	56	1	55	36	5	96	91	12	9	7	9	16
	22	18	20	1	19	14	5	38	33	8	3	3	3	6
	23	20	21	1	21	16	5	42	36	8	4	4	4	7
	24	28	46	1	46	23	5	74	69	10	8	5	7	13
CB2				1	42	-5	5	0	38			-5	6	2
	1	14	28	1	27	9	5	41	36	7	6	3	5	8
	2	20	43	1	42	16	5	63	58	9	8	5	8	12
	3	14	29	1	28	10	5	43	38	7	6	3	6	8
	4	19	51	1	50	15	5	70	65	9	9	4	9	13
	5	23	56	1	55	18	5	79	73	9	10	4	9	13
	6	14	17	1	17	10	5	32	27	7	3	3	3	5
	7	20	50	1	50	15	5	70	65	8	9	4	8	12
	8	11	26	1	26	7	5	38	33	7	5	2	4	7
	9	16	25	1	24	11	5	40	35	7	5	3	4	7
	10	24	42	1	41	19	5	65	60	9	8	4	8	12
	11	21	44	1	44	17	5	65	60	9	8	4	7	11
	12	21	58	1	58	17	5	80	75	8	9	4	9	12
	13	21	49	1	49	16	5	70	65	9	9	4	9	13
	14	18	34	1	34	14	5	52	47	8	6	4	6	9
	15	21	17	1	17	16	5	38	33	9	3	4	3	7
	16	25	46	1	46	21	5	72	67	9	8	5	7	12

CB3	17	31	44	1	44	26	5	75	70	10	8	5	8	13
	18	13	17	1	17	8	5	30	25	7	4	2	3	5
	19	16	19	1	19	11	5	35	30	8	3	3	3	6
	20	19	44	1	43	15	5	63	58	8	7	3	6	10
	21	22	30	1	30	17	5	52	47	9	6	4	5	9
	22	22	25	1	24	18	5	47	42	9	5	4	5	9
	23	22	46	1	45	17	5	67	62	9	7	4	7	11
	24	21	34	1	34	16	5	55	50	8	6	4	6	10
				1	36	-5	5	0	31			-5	6	1
	1	16	21	1	20	12	5	37	32	9	4	5	4	9
	2	13	25	1	25	9	5	38	33	8	6	3	6	9
	3	11	18	1	17	7	5	29	24	7	4	3	3	6
	4	13	17	1	16	8	5	30	25	8	4	4	4	7
	5	13	34	5	30	9	5	48	38	8	10	3	5	8
	6	17	22	1	22	13	5	39	34	9	5	4	4	9
	7	17	30	1	29	12	5	46	41	8	6	4	6	9
	8	11	18	5	14	7	5	30	21	7	8	2	3	6
	9	17	50	1	50	12	5	67	62	8	9	4	8	12
	10	13	11	1	10	9	5	24	19	8	2	4	2	6
	11	36	24	1	23	32	5	60	55	12	5	8	5	12
	12	11	26	1	26	7	5	38	33	7	6	2	5	7
	13	16	22	1	22	11	5	38	33	8	4	4	4	7
	14	17	12	1	12	13	5	30	24	9	3	4	3	7
	15	13	36	1	35	8	5	48	43	7	8	2	7	10
	16	17	32	1	31	12	5	48	43	9	6	4	5	9
	17	21	0	1	0	17	5	21	17	10	0	5	0	5
	18	14	0	1	0	9	5	14	9	7	0	3	0	3
	19	12	7	1	7	8	5	19	14	7	5	2	5	7
	20													
	21	19	20	1	20	15	5	40	34	9	4	4	4	8
	22	16	20	1	19	11	5	36	30	8	5	4	5	8
	23	20	26	1	25	15	5	46	40	9	6	4	5	9
	24	12	10	1	9	8	5	22	17	7	3	3	2	5
					20								4	

4.8. Onion spread at seedling stage (OA) and mature stage (OB) with 0 (OT), 5 (OA1 and OB1), 10 (OA2), 20 (OA3 and OB2) 40 (OB3) kg m⁻² of ash

	poids frais	poids sac	poids frais- sac	poids sec	poids sec- sac
OT	1	9	5	5	6
					1

	2	15	5	11	6	2
	3	22	5	17	7	2
	4	23	5	18	7	3
	5	21	5	17	7	2
	6	29	5	24	9	5
	7	25	5	20	7	3
	8	25	5	20	7	3
	9	25	5	20	8	4
	10	28	5	24	7	3
	11	22	5	17	7	2
	12	21	5	16	7	2
	13	16	5	11	6	2
	14	23	5	18	9	5
	15	22	5	17	7	2
	16	17	5	12	7	2
	17	8	5	4	6	1
	18	12	5	7	6	1
	19	11	5	6	6	1
	20	14	5	9	6	2
	21	14	5	10	6	2
	22	17	5	12	6	2
	23	20	5	15	10	6
	24	27	5	23	7	3
	25	20	5	16	7	2
	26	20	5	16	10	5
	27	25	5	20	7	3
	28	31	5	27	8	3
	29	33	5	28	8	4
	30	29	5	25	11	6
				16		
OA1	1	14	5	9	6	2
	2	8	5	3	6	1
	3	15	5	10	7	2
	4	40	5	35	9	4
	5	19	5	15	7	3
	6	35	5	30	8	4
	7	15	5	10	6	2
	8	11	5	6	6	1
	9	10	5	5	6	1
	10	13	5	8	6	1
	11	11	5	7	6	1
	12	16	5	12	7	2
	13	9	5	5	6	1

	14	13	5	8	6	2
	15	7	5	3	5	1
	16	22	5	17	7	3
	17	22	5	17	8	3
	18	12	5	8	6	2
	19	24	5	19	8	4
	20	25	5	20	8	3
	21	21	5	16	8	3
	22	14	5	9	6	2
	23	12	5	7	6	2
	24	20	5	15	7	3
	25	20	5	15	7	3
	26	32	5	27	11	7
	27	22	5	18	8	3
	28	8	5	3	6	1
	29	9	5	5	6	1
	30	8	5	3	6	1
				12		
OA2	1	16	5	11	7	2
	2	17	5	12	7	2
	3	17	5	13	7	2
	4	16	5	12	7	2
	5	23	5	19	8	3
	6	20	5	15	7	2
	7	19	5	14	7	2
	8	18	5	13	7	2
	9	20	5	15	7	3
	10	10	5	6	6	1
	11	12	5	7	6	1
	12	10	5	6	6	1
	13	16	5	11	7	2
	14	27	5	22	8	4
	15	20	5	15	8	3
	16	20	5	15	7	2
	17	18	5	13	7	2
	18	14	5	10	6	2
	19	24	5	19	7	2
	20	14	5	9	5	1
	21	20	5	16	7	2
	22	14	5	9	6	2
	23	12	5	8	6	2
	24	10	5	5	6	1
	25	14	5	10	7	2

	26	13	5	9	6	2
	27	10	5	5	6	1
	28	14	5	9	7	2
	29	15	5	10	7	2
	30	12	5	7	6	2
				11		
OA3	1	21	5	16	7	3
	2	22	5	17	7	3
	3	12	5	7	6	2
	4	18	5	13	7	3
	5	18	5	13	7	2
	6	17	5	12	7	2
	7	17	5	12	7	2
	8	15	5	10	7	2
	9	19	5	15	7	2
	10	8	5	3	6	1
	11	8	5	3	6	1
	12	9	5	5	6	1
	13	23	5	18	8	3
	14	28	5	24	8	3
	15	14	5	10	6	2
	16	14	5	9	6	1
	17	17	5	12	7	2
	18	12	5	7	6	1
	19	13	5	8	6	1
	20	22	5	17	7	3
	21	30	5	25	9	4
	22	20	5	15	7	2
	23	17	5	12	7	2
	24	23	5	19	7	3
	25	8	5	4	7	2
	26	10	5	5	6	1
	27	12	5	7	6	1
	28	14	5	9	6	2
	29	13	5	8	6	2
	30	8	5	4	6	1
				11		
OB1	1	8	5	3	6	1
	2	13	5	8	6	1
	3	13	5	9	6	1
	4	9	5	4	6	1
	5	10	5	6	6	1
	6	10	5	5	6	1

	7	10	5	6	6	1
	8	14	5	9	6	1
	9	15	5	11	6	2
	10	11	5	6	6	1
	11	13	5	8	6	1
	12	14	5	9	6	2
	13	20	5	16	7	2
	14	12	5	7	6	1
	15	18	5	13	6	2
	16	12	5	7	6	1
	17	18	5	14	7	2
	18	10	5	5	6	1
	19	32	5	27	8	3
	20	8	5	4	5	1
	21	28	5	23	7	3
	22	18	5	13	7	2
	23	23	5	19	7	2
	24	26	5	22	7	2
	25	18	5	13	6	2
	26	13	5	8	6	1
	27	12	5	7	6	1
	28	29	5	25	7	3
	29	14	5	9	6	2
	30	16	5	11	7	2
				11		
OB2	1	8	5	4	6	1
	2	13	5	9	6	1
	3	16	5	11	6	2
	4	15	5	10	6	1
	5	16	5	11	6	2
	6	15	5	10	6	1
	7	11	5	6	6	1
	8	12	5	7	6	1
	9	11	5	6	6	1
	10	19	5	14	6	2
	11	9	5	4	6	1
	12	20	5	15	6	2
	13	12	5	8	6	1
	14	16	5	12	6	2
	15	26	5	22	8	3
	16	15	5	11	6	1
	17	16	5	12	6	2
	18	15	5	11	6	1

	19	22	5	18	7	2
	20	19	5	14	7	2
	21	28	5	23	8	3
	22	17	5	13	6	2
	23	26	5	21	7	3
	24	27	5	23	7	3
	25	12	5	8	6	1
	26	15	5	10	6	1
	27	16	5	12	6	2
	28	14	5	10	6	1
	29	17	5	12	6	2
	30	16	5	12	6	2
				12		
OB3	1	19	5	15	7	2
	2	18	5	13	7	2
	3	12	5	7	6	1
	4	18	5	14	7	2
	5	18	5	14	7	2
	6	23	5	18	7	2
	7	16	5	12	6	1
	8	18	5	14	7	2
	9	23	5	18	7	2
	10	31	5	26	8	3
	11	23	5	18	7	2
	12	21	5	17	7	2
	13	15	5	11	6	2
	14	8	5	4	5	1
	15	18	5	14	7	2
	16	27	5	22	7	3
	17	13	5	9	6	1
	18	36	5	31	8	4
	19	20	5	15	7	2
	20	29	5	24	8	3
	21	14	5	10	6	1
	22	20	5	15	7	2
	23	21	5	16	7	2
	24	33	5	29	8	3
	25	17	5	13	7	2
	26	24	5	19	7	3
	27	12	5	7	6	1
	28	32	5	27	8	3
	29	18	5	14	7	2
	30	22	5	17	7	3

16,04

4.9. Fresh weight loss of lettuce, cabbage, onions, carrots at seedling and mature stages when exposed to ash load 0,5,10,20 and 40 kg m⁻²

	ash load	poids frais moyen	perte (g)	perte (%) *100	100-	
Seedling lettuce	0	152	0	0	0	100
Seedling lettuce	5	138	14	0	9	91
Seedling lettuce	10	135	17	0	11	89
Seedling lettuce	20	102	50	0	33	67
	30 NA	/	/	/	NA	
	40 NA	/	/	/	NA	
Mature lettuce	0	128	0	0	0	100
Mature lettuce	5	97	31	0	24	76
Mature lettuce	10	64	64	0	50	50
	20					
Mature lettuce	30	43	85	1	66	34
	40					
Seedling cabbage	0	414	0	0	0	100
Seedling cabbage	5	273	142	0	34	66
Seedling cabbage	10	223	191	0	46	54
Seedling cabbage	20	185	229	1	55	45
Mature cabbage	0	380	0	0	0	100
Mature cabbage	5	371	9	0	2	98
Mature cabbage	10	342	38	0	10	90
	20					
Mature cabbage	30	296	84	0	22	78
Seedling carrot	0	48	0	0	0	100
Seedling carrot	5	44	4	0	9	91
Seedling carrot	10	35	13	0	27	73
Seedling carrot	20	33	15	0	32	68
Mature carrot	0	48	0	0	0	100
Mature carrot	5	42	6	0	12	88
	10					
Mature carrot	20	36	12	0	25	75
	30					
Mature carrot	40	20	28	1	58	42
Seedling onion	0	16	0	0	0	100
Seedling onion	5	12	4	0	25	75
Seedling onion	10	11	5	0	29	71

Seedling onion	20	11	5	0	30	70
Mature onion	0	16	0	0	0	100
Mature onion	5	11	5	0	33	67
	10					
Mature onion	20	12	4	0	26	74
	30					
Mature onion	40	16	0	0	1	99

Appendix 5. Other generated graphs from R

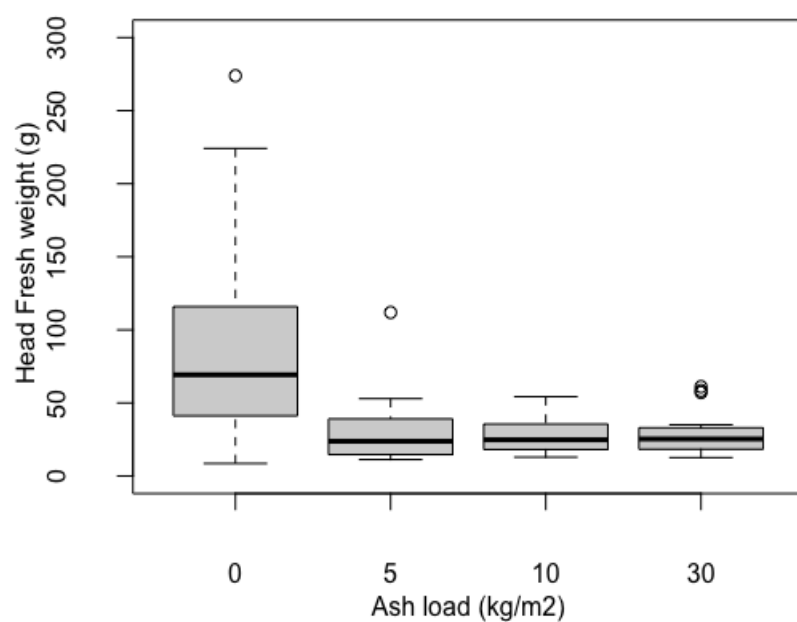


Figure A-4. Evolution of the fresh weight of cabbage's heads spread with 0, 5, 10 and 30 kg m⁻² of ash at mature stage.

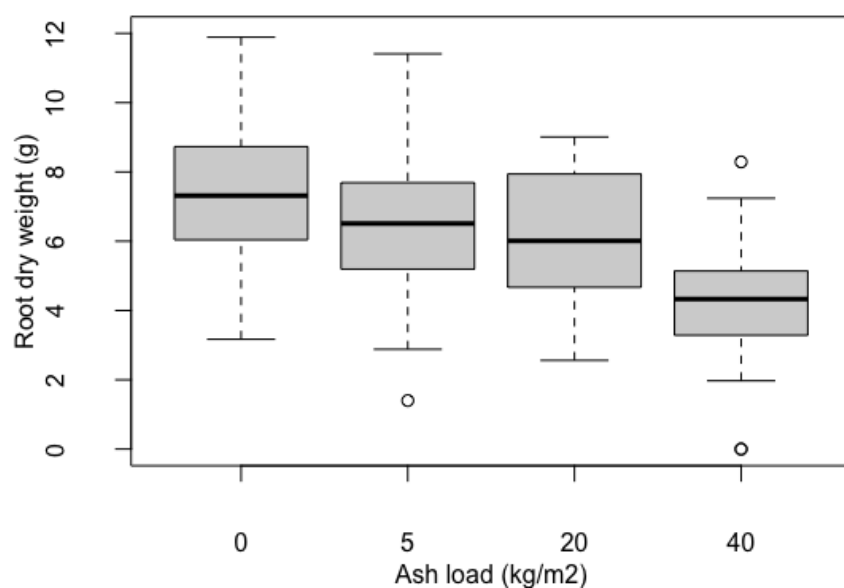


Figure A-5. Evolution of the dry weight of carrot roots spread with 0, 5, 20 and 40 kg m⁻² of ash at mature stage.

Quantifying crop vulnerability to ash fall

Presented by Pierre Miny de Tornaco

Summary:

Volcanic explosive eruptions eject large quantities of magma and silicate rock fragments into the atmosphere known as tephra. These tephra particles can reduce agricultural production by damaging crops. The type and severity of impacts to agricultural systems from tephra fall are dependent on both the intensity of tephra fall and the crop vulnerability. It is, therefore, necessary to understand and quantify the relationship between these two parameters to assess accurately tephra impact on crops thus, to manage better the risk of crop yield loss. The aim of this work is to contribute to provide vulnerability data of different crops when exposed to tephra fall in controlled conditions.