The use of Crop Residues on the Farm

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1.0. Introduction

The use of crop residues is a valuable agricultural practice, with potential benefits in terms of soil quality and fertility, nutrient and water management, and pest management (Table 1). Crop residues consist of leaves, twigs, pods and other plant litter that are left or applied on the field, prior to, concurrently, or after planting a new crop in the field.

After application, crop residues provide a physical layer on top of the soil surface that protects the soil from the elements (such as temperature, light, and water), may provide a barrier to smother weed growth, protect the soil from erosion caused by wind or heavy rainfall events, and may serve as a refuge for beneficial organisms. Residues in the soil help to reduce runoff of nutrients and sediments, and reduce irrigation requirements, by reducing evaporation rates (Silva and Moore, 2017). As residues decompose they contribute organic matter to the soil, as well as nutrients, improving over time, soil tilth and fertility. As residues decompose, they also serve as a source of metabolic energy and nutrients for microorganisms and soil arthropods, contributing to recycle nutrients in the soil, and thus help to increase biodiversity and the activity of beneficial organisms in the soil (Tian et al., 1993).

As residues decompose and degrade in the soil, the different organic compounds within the residues decompose at different rates over time. Residues from different plants, such as from grasses or broadleaf species, have distinct chemical compositions, equivalent to a chemical "fingerprint," with each compound having different rates of decomposition, physiological activity, and biochemical reactions in the soil. Thus if residues from two or more plant species are mixed and applied to the soil, instead of relying on a single species, the residues from each particular plant species may provide unique extracts and benefits to the soil, and a different timeline in terms of its degradation, contribution of organic matter to stimulate biological activity, and also spread out the release of nutrients over time, to better match the crop nutrient demands, during the growing season. Because biological diversity is believed to promote ecological stability and resiliency, an increased crop vegetational diversity, as well as residues species diversity, may thus lead to an improved "biological buffer" in the soil, and to overall system resiliency (Gilbert et al., 1969; Nicholls and Altieri, 2004).

Nutrient mineralization or breakdown refers to the release of nutrients over time, such as Nitrogen or micronutrients, as residues decompose in the soil. For instance residue degradation and nutrient mineralization may be relatively slower with residues that are more woody, such as twigs or branches, while mineralization occurs more readily on succulent plant parts such as leaves or green tissues. Thus, with a more precise knowledge about degradation rates, nutrient mineralization rates, and other characteristics, it becomes easier to make timely decisions as to the type of residues to apply depending on the field history, soil type, growing season, environmental conditions, and subsequent crop in the rotation. Farmers can also choose what plant residues to use based on individual needs such as moisture conservation, manage weeds, soil improvement, or as a nutrient amendment.

The use of plant residues is an integral part of indigenous agricultural and agroforestry systems, such as in Africa and Latin America, where subsistence farmers may lack the ability to purchase external fertilizers (Bocco, 1991; Vanlauwe et al., 1996; Gurebiyaw et al., 2019). For example indigenous farmers in Fandou Beri on Southwestern Niger lay millet stalks on fields after harvest in October, along with branches from nearby trees and shrubs, and are left in the field until planting the following February, where crops are planted among the plant residues. Research on these, or similar soils showed that these practices helped to reduce wind erosion; increased termite activity which help in soil build-up and carbon cycling; helped to break up hard surfaces in difficult arid soils; improved water infiltration and soil fertility; improved water availability; improved Phosphorus availability; decreased peak temperatures by 4C; protected seedlings during the early growth stages; and thus provided several benefits other than the direct nutrient contributions to the cash crop (Warren et al., 2002). A detailed profile of traditional mulching practices followed by indigenous Hawaiians is provided by Levin (2003).

Plant residues are also regularly used on home-gardens, and provide a number of benefits including weed control, improved soil fertility and organic matter content, conserve moisture during dry periods, reduce soil temperature during hot spells, prevent soil erosion, create a barrier between the soil and vegetables to prevent disease infestation, and allow a quicker access or re-entry to the garden after a heavy rainfall event (McCall and Nakagawa, 1980ab; Williams, 1997).

Nevertheless, growers also need to be aware of potential risks problems that may occur from the use of crop mulches or residues, such as the spread of diseases during wet periods, nutrient immobilization (such as Nitrogen tie-up), allelopathic or phytotoxic effects on cash crops, or causing pest, slug, and rodent outbreaks in the farm (Table 2).

Table 1. Potential benefits provided by Crop Residues

- Conserve moisture by reducing the amount of water loss through evaporation, particularly at 0-15 cm soil depth.
- Improved crop Water Use Efficiency under dryland conditions (Zandstra, 1982)..
- Organic mulches serve as insulators, keeping the soil cooler during the summer, and warmer during the winter.
- Residues help minimize soil temperature fluctuations.
- Mulches may reduce temperature in soil surface by up to 15C at the surface or 5C at 15 cm soil depth (Zandstra, 1982).
- Residues protect the soil from erosion, and improve water infiltration.
- Thick layers of mulch help to smother weed growth, especially in relatively weed free soils, preventing new infestations.
- Residues serves as a source of nutrients for plants
- Residues help to buffer the soil pH
- Residues help to improve the soil tilth and structure.
- Residues improve the nutrient content in soils, providing nutrients for uptake by the current or follow-up crops.
- Improved crop yields under mulch than without mulch (Zandstra, 1982).

(Demchak, 2003; Williams, 1997; Zandstra, 1982).

Table 2. Potential problems with the use of crop residues

- Tie-up Nitrogen when residues with a high C:N ratio are applied
- More difficult to prepare crop nutrient budgets and to predict nutrient release rates over time, as this is crop species, field history, and micro-environment specific.
- Poor plant stand establishment on following crop (Dabney et al., 1996)
- Increased disease incidence (such as Pythium, Rhizoctonia and Sclerotium) on subsequent crops (Dabney et al., 1996; Bonanomi et al., 2007)
- Difficulty to hand-weed in between the rows, when surface-residues have been placed
- Possible pest outbreaks such as wireworms, Chinese Rose beetles and slugs under moist and high organic matter conditions
- Allelopathic or phytotoxic effects on cash crops (Dabney et al., 1996)
- Increased release of phytotoxic chemicals during periods of flooding or anaerobic conditions (Bonanomi et al., 2007)

2.0. Composition and Degradation of Crop Residues

A natural process of decomposition begins when residues are applied to the soil, resulting in the release of a host of chemical byproducts or substrates that are volatilized, or become incorporated into soil fauna and in the soil. Chemicals released from the decomposition of organic residues include fats, waxes, carbohydrates, organic acids, alcohols, lignins, proteins, minerals, and a host of other constituents. The general decomposition process of organic residues in the soil may be divided into two phases. In the first phase, the more easily degradable substances, such as sugars, amino acids and proteins are degraded into a host of chemical substrates. In the second phase, less easily degradable products, such as lignin, tannins and cellulose are further converted into humus, a more stable form of organic matter (Bollag et al., 1998).

Overall, only a small portion of applied crop residues will eventually convert to humus. After one year of application, about 70% of crop residues will be converted to CO_2, while 5-10% will be converted to new biomass. This newly developed biomass will decompose more slowly, some of which is converted into humus. Humus in itself undergoes a very slow decomposition, of only 2-5% per year, but these levels are normally replenished as part of the new formation of humus that occurs on an ongoing basis in the soil (Bollag et al., 1998).

The several chemical components in residues have different degrees of recalcitrance or “resistance” to decomposition or degradation from microbial activity. The three most abundant components of plant residues in decreasing order are cellulose, hemicellulose, and lignin, with lignin being the most resistant to microbial decomposition. Phenolics are aromatic organic compounds that are a component primarily of lignin. Phenolic compounds require more specialized enzymatic systems for their metabolism by microbes that specialize on lignin degradation, especially lignolytic basidiomycetes, such as white rot fungi (Sjögersten et al., 2003). Phenolics play a role in the formation of humus, as they are decomposed in the soil by manganese oxides, leading to the formation of semiquinone and subsequently to humic macromolecules (Bollag et al., 1998). Most of the allelopathic or phytotoxic compounds released by plant residues are also phenolic acids, which may cause nutrient or hormonal imbalances and alter the cell wall structure of plants (Stirzaker and Bunn, 1996). Some phenolics have also been shown to be toxic to insects, fungi, bacteria, nematodes and weeds (D'Addabbo et al., 2014).

As an indication of its resistance to decomposition, when residues are composted, lignin represents about 45-50% of the finished composted material, with a significant level of phenolics that remain after the degradation process (Serra-Wittling et al., 1996). Compounds of residues that are often listed in the crop production literature include lignin, polyphenols, Nitrogen, Silicon (such as silicon dioxide), and phosphorus tissue levels (e.g., see Constantinides and Fownes, 1994; Giller et al., 1997; Köpke, 1996; Ståhl, 2005; Tian et al., 1993)

Broadly, the chemical constituents of residues and their resistance to microbial decomposition may be divided into six main categories: (1) cellulose, about 15-60% of the dry weight of residues; (2) hemicelluloses (10-30%); (3) lignins (5-30%); (4) water-soluble sugars, amino acids, and aliphatic acids (5-30%); (5) ether- and methanol-soluble fats, oils, waxes, and pigments; and (6) nitrogen- and sulfur-containing proteins. Of these components, cellulose, hemicelluloses, and proteins are degraded more easily by microbial activity, while lignins, lipids, and tannins are more resistant to decomposition. The easily degradable components are converted to CO_2 by microorganisms as a source of carbon and energy, while nitrogen (N) is mineralized in the form of ammonium or nitrates (Bollag et al., 1998).

As part of the degradation process, residues also release volatile compounds, such as acetaldehyde, iso-butyraldehyde, and isovaleraldehyde, 2-methylbutanal which stimulate microbial activity in the soil, indicating the potential that volatiles may play in pest management and the microbial ecology of the soil (Owens et al., 1969; Sangeetha and Baskar, 2015).

When residues are applied on the soil, under the proper environmental conditions consisting of temperature, moisture, and oxygen availability, residues are fed upon by microbial organisms and microfauna (such as bacteria, molds, worms, insects), which enhances the degradation process, and subsequent release of chemicals such as carbon (C), nitrogen (N), phosphorous (P), and potassium (K) which become available as nutrients for plant uptake (Hortenstine, 1981). Degradation products from crop residues such as nitrogen (N), cellulose, lignin and polyphenols play a role in the rate of nutrient release from residues and thus with the subsequent rate of nutrient uptake by cash crops (Rasche et al., 2014).

The presence of earthworms enhances nutrient cycling and the degradation of residues in the soil. An early growth chamber study showed that earthworms enhanced the degradation of surface residues by 30%, as compared to control treatments without earthworms (Zachmann and Linden, 1989).

Elevated levels of polyphenols and other secondary components in root and leaf tissues will slow down the degradation process and release of nutrients, but promotes mycorrhizal fungal activity (Moura et al., 2016). An evaluation of rates of decomposition of three species used with shifting cultivation in Papua Guinea determined that the lignin plus polyphenols over Nitrogen tissue levels (lignin plus polyphenol:Nitrogen ratio) best predicted the rate of species residues decomposition (Hartemink and O'Sullivan, 2001).

Residues are degraded by primary and secondary decomposers, resulting in soil formation. Primary decomposers consist of micro-fauna such as beetle larvae, centipedes, millipedes, and termites in tropical soils, along with saprophytic fungi and protozoa which produce extracellular enzymes that help dissolve the outer protective tissues (Tian et al., 1993). Secondary decomposers consist primarily of saprophytic bacteria and fungi, which selectively degrade larger organic molecules such as lignin and cellulose (Bollag et al., 1998). Microbial organisms such as bacteria, fungi, and protozoa are also drivers of energy and nutrient cycles in the soil (Hättenschwiler et al., 2005).

Researchers conduct studies to determine the chemical degradation process of crop residues, as well as their nutrient profile, under particular growing conditions (Table 3). For example, an analysis of residues used as part of an alley crop agroforestry project conducted with legumes in Kauai, showed a range of Nitrogen of 1.4 to 3.4%, and lignin content ranging from 8.6 to 18.3%. The Kauai study found that polyphenol levels were greater in the leaves than in the twigs, with overall average levels in the litter ranging from 1.4 to 4.1%, among the several legume species (Oglesby and Fownes, 1992). Chemical constituents of *Gliricidia* tissue residues, a popular agroforestry legume species, based on research conducted in multiple locations include a Nitrogen range of 2-5%, lignin 6-15%, and polyphenols with a range of 1-2.6% (Hartemink and O'Sullivan, 2001).

Table 3. Percent of lignin in plant residues (dry weight) of several plant species (also see Matos et al., 2011)

- Acacia auriculiformis, (10.8 fresh weight; 31.1 dry weight), (Constantinides & Fownes, 1994)
- Acioa, 47.6 (Tian et al., 1993)
- Alfalfa,1st pick, 5% (Köpke, 1996)
- Alfalfa, 3rd pick, 6% (Köpke, 1996)
- Calliandra calothyrsus (6.4 fresh; 11.7 dry weight), (Constantinides & Fownes, 1994)
- Cassia tree, Senna siamea, 25 (Ståhl, 2005), (Constantinides & Fownes, 1994)
- Casuarina equisetifolia (13.7, fresh weight; 16.1 dry weight), (Constantinides & Fownes, 1994)
- Coconut, Cocos nucifera, (13.5, fresh, leaves; 18 dry weight), (Constantinides & Fownes, 1994)
- Corn, stover, 6.8 (Tian et al., 1993)
- Cotton, 13% (Univ. Calif., 2005).
- Eucalyptus camaldulensis, (10.2 fresh weight; 14 dry weight), (Constantinides & Fownes, 1994)
- Eucalyptus camaldulensis, 25 (Ståhl, 2005)

- Eucalyptus tereticornis, 32 (Ståhl, 2005)
- Faba bean, immature, 8%; mature, 23% (Köpke, 1996)
- Gliricidia sepium, 7.2 fresh weight leaves only; 11.9 dry weight), (Constantinides & Fownes, 1994); 11.6 (Tian et al., 1993); 15%, dry weight leaves only (Hartemink and O'Sullivan, 2001).
- Inga edulis, (18 fresh weight leaves only; 36.3 dry weight), (Constantinides & Fownes, 1994)
- Leucaena leucocephala 29 (Ståhl, 2005), 5.9, (Constantinides & Fownes, 1994); 13.4 (Tian et al., 1993)
- Neem, Azadirachta indica, 5.1 (Fresh), (17.6 leaves, dry matter), Constantinides & Fownes, 1994)
- Peanut, Arachis hypogaea, 5.3, dry weight, (Constantinides & Fownes, 1994); tissue still green, 5% (Giller et al., 1997)
- Prosopis chilensis, 15 (Ståhl, 2005)
- Rice, straw 5.2 (Tian et al., 1993)
- Sesbania sesban, 5.6 (Constantinides & Fownes, 1994)
- Soybean (mature harvest), 10% (Giller et al., 1997)

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3.0. Practical guides for the use of Crop Residues

Some of the materials that are commonly used as crop residues include grass clippings, leaves, straw, sawdust, wood shavings, as well as aged or composted manure that has been mixed with straw, compost, or other organic amendments. When residues with a high Carbon : Nitrogen ratio are applied (C:N ratio > 30), consider adding an amendment high in Nitrogen to prevent a deficiency of Nitrogen for the follow-up crop. In addition it is important to maintain a proper level of moisture, to allow for the timely decomposition of the residues (McCall and Nakagawa, 1980a).

Average amount of crop residues that remained in the field after harvest of the crop under rainfed conditions over a period of 10 years in Southern Australia as part of a rotation with wheat, on a dry weight basis, were for wheat 3,500, Barley 3,600, Peas 2,900, Lupins 3000, and for Faba beans 3,260 Kg/Ha/Year. Average amount of rainfall over the 10 years, were 350 mm/ year (14 inches) during the growing season, as part of the rotation of wheat with each of the other crops (Schultz, 1995). The average amount of top growth fresh weight produced by several cool-season cover crops at high-elevations in Hawaii is provided by Pant et al., (2014).

To evaluate their effectiveness, it is helpful to assess the levels of residues in the field, such as those that may be left-over after harvest of the previous cash crop or cover crop in the rotation. Several methods are available to assess the levels of crop residues with different levels of precision, ranging from visual estimations to spectral determinations via remote sensing techniques (Su et al., 1994; Shelton et al., 1995; Sullivan et al., 2007). Some guidelines predict the amount of ground cover from crop residues that will be left in the field after particular mechanical field operations such as 0-10% ground cover after moldboard plowing, 5-20% after disk plowing, 40-70% after a chisel-subsoiler, 5-35% after the pass of a 6 inch deep rotary tiller; 20-60% after a 3 inch deep secondary tillage with a rotary tiller, and 10-50% residues ground cover, after a disk-subsoiler operation (Shelton et al., 1995).

One important variable to consider when applying crop residues is the Carbon to Nitrogen (C:N) Ratio, which determines how readily is Nitrogen either 'tied-up' by the residues as part of the chemical degradation process, or how readily it is released for uptake by the cash crop. If the Carbon : Nitrogen (C:N) ratio is greater than 30, then the N in the soil will more than likely become tied-up, as part of the residue microbial degradation process (Table 4). If the C:N ratio is lower than 30, then Nitrogen will likely be released into the soil, becoming available for crop uptake. After soil application, the C:N ratio of residues will slowly and steadily decline, as part of the degradation process, until it reaches a stable level of about 10:1. Initially, the C:N ratio for straw is in the range of 20:1 to 50:1, while the ratio for raw sawdust may range from 300:1 to 700:1. Growers that plan to use a residue source with a very high C:N ratio, such as sawdust, may consider amending the residues with a source high in Nitrogen, at a rate of about 11 Kg of N/ton applied, and/or by mixing it with residues that have a lower C:N ratio, such as from leguminous crops (Table 5) (Demchak, 2003; Hortenstine, 1981).

The C:N ratio of residues should also be taken into account when laying down residues of cover crops that are grown on-site, and mowed-down, for placement of the residues in the soil-surface. It is possible to choose the timing when the cover crop in the field will be mowed or turned-over, to obtain a desirable C:N ratio, and subsequent release of nitrogen for the follow-up crop. For example, with leguminous plants such as sunnhemp, pigeonpea or Sesbania, when young or immature plants are pruned or mowed down, the residues will have a relatively lower C:N ratio and thus they will decompose more quickly and release N faster than a more mature/woody plant would, as illustrated in Table 6 (Köpke, 1996). Conversely, growers may choose to mow these legumes at a more mature/woody stage, so that the residues will decompose more slowly, and protect or cover the soil, over a longer period of time. In general legumes have C:N ratios in the range of 15-25:1, while for grasses it ranges from 15-100:1. In South Florida, to reach a middle-ground, it is recommended that sunnhemp cover crops be terminated at 10-12 weeks after planting (Wang and McSorley, 2012).

When residues from non-leguminous cover crops are used, such as rye or oats, additional Nitrogen amendments may need to be applied, to account for their relatively higher C:N ratio. The residues from non-leguminous crops, such as rye, may "tie-up" about 10-15 Kg (25-30 lbs) of Nitrogen per ton of crop residues laid down in the soil. Thus, growers may select the types of residues that will be applied, including possible combinations of plant species (such as a combination of both legumes and non-leguminous species) and plant maturity stages, to apply residues that will decompose at an appropriate rate, and that will have a C:N ratio that will better match the fertility of the particular soil as well as the nutritional needs of the follow-up crop in the field. For example, a legume-grass mixture of clover and ryegrass planted in Denmark showed a 25 to 43% increased availability of Nitrogen, or 23 to 28 Kg/Ha more N as compared to the N provided from the residues of rye alone (Høgh-Jensen and Schjoerring, 1996).

In terms of the residue application rates that are recommended this will vary based on a host of variables such as the type of residues, location, time of the year, subsequent crops, and the overall purpose for their use, such as a nutrient amendment, or to establish a mulch for weed control. As a general reference, for regions where farmers often can't afford the cost of chemical fertilizers, such as in the arid West African Sahel, annual application rates of crop residues of 2,000-4,000 Kg/Ha result in considerable yield increases of 20-400%, but many subsistence farmers are unable to meet these rates, due to the many competing demands or alternative uses for crop residues in that region, such as for fuel, building materials, and feed (Lamers et al., 1998; Schlecht et al., 2006). Slight, but realistic residue application rates for Africa, to manage erosion are in the range of 0.3 kg/m2 (3,000 kg/Ha), however, even these relative low rates are often difficult to reach in subsistence agricultural systems (Schmengler, 2011).

Fields with surface crop residues, especially after the mowing of a cover crop, often result in poor stand establishment for the following crop in the rotation. Problems with stand establishment on crops planted on fields with surface residues may include poor seed-soil contact, low temperatures, poor moisture levels, ammonia toxicity, pests, slugs, diseases, and allelopathy. General recommendations to deal with poor stands, is to allow a 2-4 week period after mowing or termination of the cover crop to allow for the residues to dry, to reduce the number of any predatory or pest organisms and to allow for the leaching of any possible phytotoxic or allelopathic chemicals released by the residues (Dabney et al., 1996).

It should be recognized that the residues from some plant species may be phytotoxic or allelopathic to subsequent crops in the rotation (Cervera-Mata et al., 2017). Factors to consider to manage potential phytotoxic effects from residues, include the amount of residues that are applied or left in the field, as well as the number of days between the time that residues are applied, to the time that the next crop is planted in the field (Bonanomi et al., 2007). In cases where phytotoxic effects may occur, it may be necessary to delay planting by a week or two. Another variable to consider is that different chemical reactions occur when the degradation process occurs under flooding or anaerobic conditions, resulting in the release of potentially different and more phytotoxic materials (Bonanomi et al., 2007). While these chemicals may be phytotoxic to fungal diseases, they may also be toxic to cash crops. It is thus important to be aware of possible phytotoxic effects of residues during periods of heavy rain where anaerobic conditions may affect the residue degradation process, resulting in the release of phytotoxic chemicals, affecting the growth of current or subsequent cash crops in the field.

When the primary goal for the use of residues is to provide nutrients for the following crop, growers may need to decide whether to apply surface residues as a mulch, or to incorporate them. An experiment was conducted in central Malawi to evaluate the effect of leaf pigeonpea residues on the yield of corn. Pigeonpea leaf residues were applied at a rate of about 2,400 Kg/Ha on a dry weight basis with a 2.1% Nitrogen content. Overall corn yields were increased by about 20% (about 5,300 kg/Ha vs. 4,200 Kg/Ha) when the pigeonpea residues were incorporated, as compared to the surface-application of the residues (Sanga and Kabame, 2014).

When the purpose of crop residues is to minimize erosion risks, especially under sloped field conditions, the USDA Natural Resources and Conservation Service suggest to "Use mulching and residue management to keep the soil covered. Place slash or plant residue (such as banana stalks and tree trimmings) in strips across the slope to help trap and retain water" (Esgate et al., 2015).

Some early, and basic recommendations for the use of crop residues, and organic mulches in home-gardens on Hawaii are listed on Table 7. Several of the plant species used as crop residues or mulches by indigenous Hawaiians, along with a description of their use, is provided by Levin (2003).

Crop profiles with the use of Residues

Crop residues are often used as part of the rice-cash crop rotation system in Asia. In Java upland rice residues are spread in the field prior to the planting of soybean. The soybean crop may also be sown in the field prior to the harvest or rice. The soybean crop typically receives little or no cultivation, prior to harvest. The addition of mulch has been shown to increase the subsequent soybean yields, which was attributed to lower soil temperatures, increased soil moisture, and decreased weed growth. Similarly, in Taiwan the soybean crop is planted in the rice residues, without soil preparation. The rice straw in Taiwan is spread over the field after the soybean has been sown in shallow holes, beside each rice hill (Moody, 1982).

The use of crop residues is an integral part in the corn-mucuna production system on the highlands of northern Honduras. Mucuna is planted in between the rows, and continues to grow after the corn harvest. At about 8 months after planting the thick-growth of Mucuna plants are cut down, left as a mulch on the field, and a new corn crop is sowed among the mulch. This system results in reduced labor costs, weed control, and improved nutrient cycling, from the use of Mucuna or the "fertilizer bean" as referred to by farmers in the region. Mucuna residues and the beans also have a double use as a feed for livestock (Buckles et al., 1998).

Table 4. The Carbon to Nitrogen (C:N) ratio from residues of several legume and non-legume crops and agroforestry species, as reported in the literature.

Crop Species	C:N Ratio	Source
Rye, immature	15:1	Kessavalou and Walters, 1999
Soybean, mature (legume)	36:1	Kessavalou and Walters, 1999
Corn, mature	70:1	Kessavalou and Walters, 1999
Corn	59:1	Rasche et al., 2014
Perennial Peanut, Arachis pintoi (legume)	15.7-15.9	Matos et al., 2011
Calliandra calothyrsus	13:1	Rasche et al., 2014; (Mukuralinda et al., 2008)
Calopogonium mucunoides (legume)	12.5-13.6	Matos et al., 2011

Stylosanthes guianensis (legume)	13.6-14.6	Matos et al., 2011
Tithonia diversifolia	13:1	Rasche et al., 2014
Tithonia	9.4	Mukuralinda et al., 2008
Mucuna pruriens (Stizolobium aterrimum) (legume)	12.2-12.3	Matos et al., 2011
Canola/Rape	41.0	Butterly et al., 2013
Chickpea (legume)	36.3	Butterly et al., 2013
Wheat	76	Butterly et al., 2013
Tephrosia	14	Mukuralinda et al., 2008

Table 5. Percent Nitrogen (N) tissue content of several agroforestry species. The samples from Oglesby and Fownes, were part of an alley-crop, agroforestry study conducted in Kauai.

Residue Crop Species	Nitrogen tissue content (%)	Source
Calliandra calothyrsus	2.8%	Oglesby and Fownes, 1992
Calliandra	3.0%	Mukuralinda et al., 2008
Cassia reticulata	2.6%	Oglesby and Fownes, 1992
Cassia siamea	2.3%	Oglesby and Fownes, 1992
Gliricidia sepium	3.4%	Oglesby and Fownes, 1992
Inga edulis	2.5%	Oglesby and Fownes, 1992
Leucaena leucocephala	3.7%	Oglesby and Fownes, 1992
Leucaena leucocephala	3.0%	Ståhl, 2005
Sesbania sesban	1.4%	Oglesby and Fownes, 1992
Senna siamea	2.0%	Ståhl, 2005
Eucalyptus camaldulensis	2.2%	Ståhl, 2005
E. tereticornis	1.5%	Ståhl, 2005
Prosopis chilensis	4.2	Ståhl, 2005
Tithonia	3.3%	Mukuralinda et al., 2008
Tephrosia	2.8%	Mukuralinda et al., 2008

Note: Kauai, Hawaii: Oglesby and Fownes, 1992; Tanzania: Ståhl, 2005; and Rwanda, Mukuralinda et al., 2008.
Note: all of these values need to be treated as a general reference, and with caution. Many variables can affect the tissue N content for any given crop, and at any point in time. It wouldn't be appropriate to compare values between regions, but serve as a general reference.

Table 6. Percent degradation and chemical constituents of leguminous cover crops mowed at an immature stage and at a ripening stage. Percent decay of residues was determined at 90 days after incubation, to determine levels of residue decomposition from either young (immature) or older (more mature) plant residues (adapted from Köpke, 1996).

Crop	Decay after 90 days (%)	Nitrogen (%)	C:N ratio	Lignin (%)
Faba bean, immature	44	3.8	11	8
Faba bean, mature	31	1.2	41	23
Alfalfa, first pick	63	2.1	21	5
Alfalfa, third pick	74	1.9	23	6

(adapted from Köpke, 1996)

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Table 7. Early mulching recommendations for home-gardens in Hawaii (McCall and Nakagawa. 1980ab).

- Apply mulch on “tall vegetables” such as Tomatoes, peppers, eggplants, broccoli, cauliflower, when the plants are 6-8 inches tall.
- On vine crops, such as cucumber, melons, and squash, apply mulch 3 to 5 inches deep extending from the base (stem) of the plant and cover the soil as far as the vines extend
- For root crops such as carrots, and beets, make sure not to cover the tops with the mulch. Apply a mulch 2 to 3 inches thick, and remove the mulch during harvest,

(McCall and Nakagawa. 1980ab).

4.0. Crop Residues Effects on Soil Quality

4.1. Residues Effects on soil quality and Organic Matter
The mineralization or breakdown of crop residues, releases nutrients, increases the soil organic matter content, which increase the soil Cation Exchange Capacity- and thus residues improve nutrient cycling within the farm. The soil organic matter, for its part, serves as a long-term bank or reservoir of nutrients and also promotes a greater fauna and microbial activity in the soil, which optimizes biological processes, such as nutrient cycling and biological pest control. The long-term objective of increasing the soil organic matter content, is to build up the humus content in the soil. As discussed earlier, humus represents the more stable fraction of organic matter that remains after residue decomposition.

Early long-term research with no-till farming and residue management in temperate areas indicated that after 10 years of surface residues the average annual increases in soil organic matter (OM) content ranged from 200 to 1500 lbs/Acre/year, with levels varying depending on the amount of residues left on the surface, on the incorporation of cover crops into the rotation, and on the amount of rainfall received, in arid regions (Moldenhauer et al., 1995). Early research over 10-20 years also indicated that surface residues increased the soil organic matter content to over 10% on the top 1 inch of soil, which researchers believed to be more effective in decreasing evaporation and in increasing water infiltration than if this OM buildup had been mixed over the top 8-10 inches of soil (Moldenhauer et al., 1995).

Because roots tend to have a higher proportion of lignin and suberin, Carbon mineralization (breakdown) or degradation, into CO_2, is in general 20-30% lower in roots than residues obtained from leaves and stems. Thus, as Carbon from the roots becomes incorporated into the soil, it is likely to contribute proportionally more to the buildup of organic matter in the soil than residues from leaves or stems (FAO/IAEA, 2008). Crop residues can make important contributions to the soil Carbon (C) pool, especially in soils with low organic matter content. For example, in Sri Lanka, crop residues from *Gliricidia* contributed 36% of the soil Carbon pool, 4 weeks after application, and 31% by the time of corn harvest. Because this percent contribution to the soil C pool declines over time, especially in tropical climates, periodic residue applications would be required to maintain soil C levels (FAO/IAEA, 2008).

Crop residues used as part of no-till farming, or applied as mulches are recommended to improve soil quality, especially on the top 15 cm of the soil layer. Benefits of mulches or surface residues include to protect from the impact of wind or rain, and to reduce evapotranspiration, which may reduce soil drying and compaction (Nordstrom and Hotta, 2004; Moura et al., 2016). Overall benefits provided by crop residues when used as organic mulches to cover and protect the soil surface from the elements include improved soil structure, soil aggregation, water infiltration, water-holding capacity, water content, aeration and permeability, increased rooting depth, decreased soil crusting and bulk density, increased soil pH (with exceptions), and cooler soil temperatures (Valenzuela, 2000). When residues were applied at rates of 2-8 MT/Hectare it resulted in improved soil aggregate formation, soil porosity, and soil moisture under soil field capacity. In turn, the improved soil structure results in improved nutrient uptake by plants, and in less leaching of Nitrogen (Moura et al., 2016).

Through the decomposition process, residues improve the soil tilth or structure. The degradation of residues into small organic particles results in the formation of soil aggregates. The soil aggregates in turn improve the soil moisture content, as well as its porosity, thus making both water and oxygen more available for root and plant growth. Soil aggregates also improve the soil structure, and make the soil more resistant to erosion. The microbial activity in the soil, is in general correlated with the degree of soil aggregation (Degens, 1997). Microbial activity, in terms of soil aggregation, includes the role played by several fungal species, including mycorrhizae which assist in the soil aggregation process, through the release of binding or mucilaginous agents such as glomalin and polysaccharides (Rillig and Mummey, 2006).

The effects of crop residues on aggregate stability were evaluated in a no-till experiment conducted in Georgia. Under the no-till system the level of applied crop residues were 13.2 as compared to 6.3 Mt/Ha under the conventional cultivated system, resulting in soil Carbon contents of 23.7 and 11 gr/Kg of soil, respectively; and in water stable aggregate values of 88.5% in the no-till system with crop residues, vs 58% under the conventional tilled system (Wagger et al., 1998).

The effects of surface residues on soil fertility and carbon sequestration were evaluated in sugarcane fields of Southern Brazil, at several locations 4 and 12 years after conversion from burning the residues prior to harvest to mechanized green-trashing (leaving surface residues in the field). Overall, the surface residues increased the amount of residue biomass left in the field by about 13 tons/Hectare. With the surface residues, the amount of Carbon sequestered in the soil increased by about 1 ton/Ha, while the amount of Nitrogen in the soil increased by about 110 Kg/Ha. The levels of other nutrients also increased in the top soil layers in the fields with surface residues. Effects on soil quality parameters after the conversion from pre-burning to leaving residues in the soil surface included, increased soil bulk-density (reflecting a relatively lower soil clay content), improved overall soil aggregation, improved macro-aggregation (resulting in larger pore sizes, for water and oxygen movement), as well as increased Calcium and Magnesium levels, increased Cation Exchange Capacity, increased base saturation, and a small increase in the soil pH (Luca et al., 2018).

The overall rate of residue decomposition, and its contribution to the soil organic matter content, will depend on the chemical composition of the roots, leaves, and stems from the applied residues. With so-called ‘good quality’ residues rich in nutrients and low in Carbon, nutrients will quickly mineralize for crop uptake, but these more succulent residues will not contribute considerably to the organic matter content of the soil. On the other hand, residues with greater levels of lignins and other high molecular weight polyphenols, such as tannins, will degrade more slowly, and contribute proportionally more to the long-term soil organic matter content (Moura et al., 2016). Thus residues from succulent legumes in general degrade faster, due to their relatively higher Nitrogen content, while grasses, or woody residues, which have a higher C:N ratio, degrade more slowly over time, and thus make a greater long-term contribution to the soil organic matter content. Growers will thus need to make decisions as to the type of residues, or mix of residues to be used on the farm, based on the particular production goals at the time. Thus green or succulent residues would be more beneficial if nutrients are needed for the following cash crop, while residues from woody plants or grasses would be more helpful to improve the soil tilth, and long-term organic matter content.

A 10-year experiment involving tillage and crop rotations indicated that the levels of crop residues that were incorporated or left in the soil surface contributed more towards the soil organic matter content, than other management practices. In general incorporation of residues enhanced decomposition rates, under tillage treatments, as compared to residues that remained in the soil surface in no-till systems (Wood and Edwards, 1992) (see Table 8 below).

Table 8. The fate of Carbon (decomposition and incorporation into soil organic matter) when plant residues are applied either as a surface residue (mulch) or incorporated into the soil. This data are based on research from France, with rape residues, under controlled environmental conditions during a 9 week period of evaluation (adapted from FAO/IAEA, 2008).

Residue Treatment	Carbon that remains as residues after 9 weeks	Residue C incorporated into the soil Carbon fraction	C evolved as CO_2
Surface-mulch	73%	7.8%	19%
Incorporated	21%	25%	55%

4.2. Erosion control with residues

The use of crop residues is an important management practice to control soil erosion (Table 9). The practice of stubble mulch management was established in the U.S. after the dust bowl period of the 1930s in the Great Plains. The goal of the stubble mulch system was to maintain residue coverage of the soil at all times (Skidmore, 1986). To protect the production base of U.S. agriculture, the Food Security Act was passed in 1985 to protect soils, including the 143 million acres of highly erodible soils, with the overall goal of ensuring food supplies for future generations. As a result, and after considerable long-term research during the 1960s and 1970s, the practice of no-till farming and crop residue management became an integral part of soil conservation efforts in the U.S. (Papendick and Moldenhauer, 1995). For example the early research indicated that erosion was reduced by 100, 83, and 30% when the residue cover of the soil reached 100, 50, and 10%, respectively. However, management strategies had to be developed to optimize the residue management system, and to address any adverse effects, and logistical or production difficulties, caused by the presence of residues on the soil (Papendick and Moldenhauer, 1995).

Because of the benefits that crop residues provide to reduce erosion rates, the practice of Organic Mulching (Practice No. 484), the use of Alley Crops and Hedgerows (Practices No. 311 & 422), and the use of crop Residues (Practice No. 329) are approved conservation practices promoted by the USDA Natural Resources and Conservation Service in Hawaii, as part of its cost-share program to assist small farmers adopt recommended soil conservation practices (Esgate et al., 2015).

Optimal residue rates to manage erosion and to contribute towards soil fertility are in the range of 20-25 MT/Ha. However even when lower residue rates of 2-6 MT/Ha are used, covering only 50% of the soil surface, erosion risk may still be reduced by 80%, compared to bare-ground fields (Schmengler, 2011). For wind erosion control, at least 1,000 Kg/Ha of small-grain equivalent levels of residues are recommended (Unger and Howell, 2000). In turn, the removal of crop residues from the field after harvest, such as from corn for use as feed, was shown to increase runoff and erosion losses (Lindstrom, 1986).

Table 9. The positive impacts contributed by surface residues, to reduce erosion rates (Moldenhauer et al., 1995; Zachmann and Linden, 1989)

- Protection from the impact of raindrops;
- Prevent soil surface sealing or impermeable layers;
- Improved water infiltration;
- Water ponds or concentration of water on the surface, infiltrates through wormholes (from earthworms) and macropores;
- Sediments concentrate on surface water ponds, preventing runoff;
- Protection of surface soil particles from wind shear or erosion (Moldenhauer et al., 1995; Nordstrom and Hotta, 2004)
- Increased earthworm activity under surface residue cover increases the stability of surface soil particles, reducing their erodibility, as well as increasing water infiltration (Zachmann and Linden, 1989)

4.3. Residues effect on soil pH

Crop residues may be used as a supplement to the application of liming materials to increase the soil pH in acid soils (Hue, 2011; Butterly et al., 2013). The crop residue amendments may help to increase the soil pH, improve the availability of Calcium in the soil, and also help reduce the toxic levels of soluble Aluminum found in acid soils.

Research with the use of crop residues has indeed shown that residues may help to reduce Alumimum toxicity in the soil, resulting in increased crop yields. Experiments were conducted in Oahu, Hawaii to determine the effect of either fresh or ashed residues from shredded pineapple or cowpea leaves, as compared to the use of standard liming $Ca(OH)_2$ treatments, on the pH of soils, Al levels, and growth of a following crop, on potted experiments. Both fresh and ashed residues were mixed with the soil, representing 1% of the soil weight, using acid Ultisol soils from Central Oahu former sugarcane fields. The control soils had a pH of 4.6 and soil solution Al levels of 21.5 µmoles/Liter. The research showed that the fresh crop residues were better able to increase the soil pH, compared to the respective use of ash residues, for each crop. Both fresh crop residues increased the pH to about 5.0, compared to 5.3 for the $Ca(OH)_2$ liming treatment. The study showed an increased soil pH with the use of fresh residues, with an average of 5.1 compared to 4.8, with the use of ash residues (Hue, 2011). With respect to the ability of the residues to reduce soluble Aluminum toxicity, the fresh residues were better at reducing soluble levels, to an average of 3.0 µmole/Liter, compared to 9.5 for the ash treatments, and 21.5 for the untreated controls. The fresh cowpea residues were the best overall treatment by reducing the soil-solution Al levels to 1.23 compared to 2.2 for the standard $Ca(OH)_2$ liming treatment. The best crop growth was obtained with the use of fresh cowpea residues, followed by fresh pineapple residues, and by the liming material (Hue, 2011).

Research conducted in Australia also showed increased soil pH following the application of residues from several plant species, and that the effect on pH depended on the type of residues used. Soil pH was improved the most with residues from chickpea and rape, with the alkalinity (concentration of cations) from the residues released within 2 weeks, but the greatest effects on the soil pH was observed 3 months after residue application. The liming effects provided by the crop residues lasted for 26 months. An increased soil pH, caused by the crop residues, was also observed at lower soil profiles, below the zone where residues were applied, indicating that soluble components released by the residues had reached subsoil layers (Butterly et al., 2013).

While it may not be practical to use crop residues alone as the sole method to resolve soil acidity problems, due to the large amount of liming material required in some tropical soils, crop residues may be used as a supplement to the use of liming materials. Because the effects of crop residues on soil pH may be short-lived in warm areas, continued residue applications will need to be made every year, to address issues of soil acidity, Calcium deficiency, and soil Aluminum toxicity in acid soils of the tropics (Hue, 2011).

4.4. Residues and Earthworm activity

Earthworms play in integral part in the decomposition of crop residues. Because of their central role within the soil ecosystem, earthworms are described as keystone species or ecosystem engineers (Hättenschwiler et al., 2005). The decomposition of residues by earthworms, results in improved nutrient and water cycles, greater nutrient content such as Nitrogen, improved microbial activity, soil structure and fertility, soil water infiltration levels, and in improved root growth (Gomez-Brandon et al., 2010; Valenzuela, 2010).

Earthworm populations and activity are increased in soils that receive periodic crop residue applications and in fields that are least disturbed by tillage operations. Residues promote earthworm activity by providing a source of food, provide refuge and a buffer from the elements and extreme weather conditions, provide protection or cover from predators, and prevent the disturbance of their burrows (Donahue, 2001). For example earthworm populations increased by 40% in fields that received residues from several species including *Gliricidia* prunings, *Leucaena*, corn stover and rice straw, with the highest numbers observed in soils with *Leucaena* residues (Tian et al., 1993).

Conventional tillage operations are detrimental to earthworm populations. The plowing of previously undisturbed soils for a period of 5 years, resulted in a decline of 70% of the earthworm populations. Similarly, a field under conventional tillage for 25 years resulted in a reduction of 85-90% of the initial earthworm population. Conversely, the application of residues is positively correlated with the population and activity of earthworms. In general residues from cereals result in greater earthworm numbers, compared to plants that leave less residues in the field (Donahue, 2001).

A meta-analysis of the literature indicated that on average the presence of earthworms in the soil increases crop yields by 25% and above ground biomass by 23%. The benefits provided by earthworms was greater in fields that received crop residues, but the benefits of earthworms declined in fields high in Nitrogen (such as from synthetic fertilizer applications). This indicates that a key contribution provided by earthworms to promote plant growth and higher yields consists of the release of nitrogen from the decomposition of plant residues and organic matter (Ke and Scheu, 2008; Van Groenigen et al., 2014).

4.5. Residues and Soil Microbial Activity

Plants provide the primary source of Carbon for soil microbial activity, in the form of carbohydrates produced via photosynthesis and released to the soil via root exudates, or through plant residues (Ishaq, 2017). As part of the degradation process, plant residues also release volatile compounds, such as acetaldehyde, iso-butyraldehyde, iso-valeraldehyde, methanol, and ethanol which stimulate microbial activity in the soil (Gilbert et al., 1969; Owens et al., 1969) and which may also inhibit the growth of disease organisms (Gamliel and Stapleton, 1993).

Crop residues applied as a surface mulch or incorporated in the soil, contribute to increase the soil organic matter content, as well as the microbial activity in the soil. The increased biological activity in the soil assists with several ecological processes, such as improved nutrient cycles, and the biological control of weeds and pests. In addition, via the microbial decomposition of residues, and release of mucilagenous materials, soil aggregation, tilth, and soil chemical and biological buffering capacity improve over time. Indicators of improved microbial activity from the application of crop residues in soils include the presence and activity of key soil enzymes that contribute to nutrient cycling such as acid and alkaline phosphatases (Phosphorus cycling), arylsulfatase (Sulfur cycling), Beta-glucosidase (Carbon cycling), and L- asparaginase (Nitrogen cycling) (Mullen et al., 1998). For example the inclusion of hairy vetch residues as part of a corn no-till system increased soil organic matter levels, bacterial activity, as well as the presence of nutrient cycling enzymes in the soil profile, as compared to the no-residue controls (Mullen et al., 1998).

Research indicates that crop residues that consist of a mixture of several plant species may result in a greater and more diverse microbial activity in the soil, as compared to residues from a single species. Thus the residue or vegetational diversity above ground is directly correlated to the microbial biodiversity below ground (Wood and Edwards, 1992; Ishaq, 2017). The increased microbial biodiversity below ground creates what is described as an improved soil biological buffer, which makes the soil habitat more resilient to environmental, chemical or physical disturbance.

A healthy microbial population in the soil, includes the activity of growth promoting microorganisms which enhance the growth of crops via the production of growth regulators such as auxins and ethylene, which are produced both by plants and by soil microorganisms. Not only growth promoting microorganisms help to improve crop growth, but they may allow plants to overcome periods of environmental stress (Ishaq, 2017). Soil microorganisms also provide a host of intricate mechanisms for the biocontrol of insects and disease pests.

Numerous research studies have found that organic farming systems, which in general have higher organic matter levels, have a greater microbial activity and diversity than conventional systems. For example, the incorporation of soil residues under an organic rotation system in India resulted in increased microbial activity, including numbers of bacteria, fungi, actinomycetes, and overall microbial biomass (Davari et al., 2012). Research has also shown that residues from cover crops also help to promote microbial activity and diversity. The increased level and diversity of microbial activity in the soil, may also be effective in the bioremediation of soils with a history of chemical contamination of pesticide use (Ishaq, 2017).

Mychorrhizae-plant associations may assist to improve crop nutrient uptake, from the mineralization/release of nutrients from crop residues. A study conducted in the Hebei Province of north China, under greenhouse conditions, identified an interaction between residue applications, earthworm activity, and crop nutrient uptake facilitated by crop-*Glomus* spp. mycorrhizae associations. The experiment showed that earthworms enhanced the mineralization of Nitrogen from wheat residues by about 48%, compared to treatments without earthworms, but this N was not taken up directly by the growing corn plants. However plants that also had a mycorrhizal fungus association resulted in an 118% increase in N uptake by the shoots, and in an 87% increased N uptake by the roots, compared to treatments without mycorrhizae, showing that the mychorrizae association facilitated the uptake of N that was mineralized through the decomposition of crop residues by the earthworms in the soil. Overall nutrient uptake by the growing plants was greatest when both the earthworms and the mychorrizae were present, and the Nitrogen uptake was decreased whether either the mychorrizae or the earthworms were not included as part of the residue decomposition process (Li et al., 2013).

5.0. Effects of Residues on Soil Nutrients

Residues used as a surface mulch or incorporated into the soil contribute organic matter as well as nutrients to the soil, for uptake by cash crops. Thus, via the mineralization (breakdown) of nutrients in the soil, crop residues may provide a partial or full amount of the nutrient budget required for the production of annual or perennial crops in the tropics.

5.1. Nutrient mineralization and C:N ratios

Even residues with a high C:N content may contribute nutrients to the soil, in the long-term. To illustrate this an experiment was conducted in California in which wood chips were mixed with soil, and placed in containers to grow almond trees. After three years in the containers, a soil analysis showed higher levels of calcium, magnesium, sodium, chloride, boron, zinc, manganese, iron, copper, carbon, phosphorus, potassium, ammonium, and organic matter, compared to containers that did not receive any wood chips. Leaf nutrient tissue analysis of the trees also showed that, after three years, soils that were treated with wood chips had higher levels of phosphorus, potassium, calcium, zinc, manganese, and iron, compared to the controls. Nitrogen and iron showed higher tissue levels in soils treated with wood chips on the fourth year after the initial treatment, as well as greater water infiltration levels (Holtz, 2004; Holtz et al., 2004).

5.2. NPK rates

In some tropical regions, especially under subsistence or semi-subsistence farming, the use of crop residues is an integral part of the nutrient management program, including a reliance on indigenous trees, for the use of crop residues (Gurebiyaw et al., 2019). Plant residues may provide a partial or total amount of the nutrient needs, under traditional production systems. For example the incorporation of soil residues under an organic rotation system in India resulted in increased levels of NPK in the soil. The nutrient levels were also greater when the rotation included a legume, as compared to cereal-only based rotations (Davari et al., 2012).

Residues from legumes or green manure crops grown in rotation with cash crops, may provide significant nutrient contributions, especially Nitrogen, to the cash crop in the rotation (Constantinides and Fownes, 1994). For example, a 5 year experiment conducted in Florida showed that corn grown in monoculture yielded an average of 48 bushels per acre, as compared to 60 bushels per acre, when corn was grown in a rotation with Sunnhemp (*Crotalaria*) (Thompson, 1981). In some of the well-drained sandy soils of Florida, where it is difficult to increase the soil organic matter content, it is recommended that crop residues be applied to the soil, on an annual basis (Thompson, 1981).

By contributing to increase the organic matter content, residues also help to improve the long-term fertility of the soil. The build-up of organic matter serves as a "bank" for nutrients, which are released over time, as a "slow-release" fertilizer. Decomposing crop residues contain most of the elements essential for plant growth, and they provide a steady supply, as the nutrients are mineralized and/or incorporated into organic matter (Moldenhauer et al., 1995).

The release of nutrients by residues also results in overall improved soil nutrient relations and in improved nutrient uptake by crops in tropical settings. Research has shown that key nutrient use efficiency indicators were improved with the use of organic mulches, such as the Nitrogen and Phosphorus Crop Recovery Efficiency, as well as both Nitrogen and Phosphorus Use Efficiency (Moura et al., 2016). As an indication of the potential nutrient contribution by residues, the total amount of nutrients released by residues from two legume cover crops used on a coffee orchard in Brazil, after 360 days were 93.0 Kg/Ha of N, 7.8 of P and 63.6 of K for *Mucuna pruriens*, and 86.2 Kg/Ha of N, 7.1 of P and 50.4 of K for *Stylosanthes guianensis* (Matos et al., 2011).

5.3. Nitrogen (N)

Research indicates that the use of organic mulches results in an improved Nitrogen Use Efficiency or crop yields per unit of N (Qin et al., 2015; Moura et al., 2016). In crop rotations the residues left in the field from the previous crop provides some levels of residual nutrients for the following crop. The amount of nutrients provided via the mineralization of nutrients from the previous crop, should thus be taken into account as part of the overall nutrient budget of the subsequent crop in the rotation. For example, to determine the mineralization or release of nutrients from crop residues as part of several crop rotation schemes, 74 experiments were conducted over a 4 year period at 10 locations in England. This research indicated that the soil supply of N after crops of sugarbeets or potatoes were about 56 Kg/Ha, while the supply of N after cereals was about 46 kg/Ha. Mineralization rates for the crops in the rotations were 37 for cereals, 53 for sugarbeets, and 63 Kg/Ha of Nitrogen for potatoes. In addition the Nitrogen uptake by cereals, as the second crop in the rotation, was 15-20 Kg/Ha greater when planted after sugarbeets or potatoes, than when cereals followed other cereals in the rotation (Webb et al., 1997). Thus, the higher levels of tissue N content, and lower C:N ratios in the broadleaf crops, may have accounted for the greater rates of Nitrogen mineralization observed in the potato and sugarbeet crops, as compared to the lower N mineralization rates observed in the cereal crops. For additional examples of the N contribution by residues of several species to the following crop, as affected by the original residue N tissue contents and C:N ratios, see Table 10.

A four year experiment incorporating rye as a cover crop in a rotation with corn and soybean showed that the rye cover crop was able to uptake or capture the residual Nitrogen from the previous crop, preventing its loss from the field by leaching. The residues from the immature rye crop, left on the field prior to the planting of the following crop in the rotation, were readily mineralized, providing a source of Nitrogen for the following crop in the rotation. Thus the use of rye as a cover crop in the rotation was effective to reduce soil erosion in the field, and its residues provided a source of Nitrogen to the following crop in the rotation, as part of the residue nutrient mineralization process (Kessavalou and Walters, 1999). The research showed that the planting of rye as a cover crop reduced the levels of residual nitrogen, after the harvest of the previous crop, by 18 to 33%, reducing the risks of leaching. The levels of N taken up by the rye cover crop ranged from 42-48 Kg/Ha in its above-ground dry matter, resulting in greater amounts of N available for the following crop in the rotation, compared to treatments that did not include a cover crop (Kessavalou and Walters, 1999).

The farmers that adopt the use of rye or other species as cover crops in the rotation, would thus need to include the Nitrogen contributed by the cover crop, as part of the overall nutrient budget, to optimize crop yields, and to minimize on-farm nutrient losses from leaching or runoff. Follow-up research since then has confirmed the value of rye and other species such as triticale, wheat, clover (*Trifolium*), and vetch (*Vicia*) as cover crops in the rotation to capture residual N from the previous crop, and to help reduce erosion. Research has also shown that when residues are left on top of the soil, rather than incorporated, that the N is released over a longer period of time, which may better meet the N needs of the following crop in the rotation (Ketterings et al., 2015).

The need to scavenge or capture Nitrogen left over from the previous cash crop is important to prevent leaching into the groundwater. A recent survey in the Mid-Atlantic region of the U.S. found that the levels of Nitrogen, left over after harvest of the previous crop averaged 253 Kg/Ha, including 115 Kg/Ha of Nitrate, with 90% of this residual N being found 90 to 210 cm (35-83 inches) deep, which would be below the reach of the following crop on the rotation (Hirsh and Weil, 2019). Research has shown that cover crop rotations with legumes can reduce Nitrate leaching by 40%, while rotations with non-legume cover crops, by 70% (Ketterings et al., 2015).

It is important to identify the rate of Nitrogen release or mineralization from crop residues, to better synchronize nutrient release rates with crop uptake demands, after residue applications in the field (Table 10). Research from humid areas in the Eastern and South Eastern U.S. showed that N accumulation by legumes ranged from about 70-170 Kg/Ha, which indicates their potential for significant N contributions to the following crops in the rotation. Reported N accumulation rates for hairy vetch, a popular legume cover crop ranged from 55 to 75 Kg/Ha. When residues from legumes, such as hairy vetch and clover were incorporated in the soil, research in the northern U.S. showed that 50% of the organic N in the legume residues were released by 4 weeks, with little additional N releases occurring beyond 10 weeks after incorporation (Ketterings et al., 2015).

The N fixation rate for several legumes used in Agroforestry systems is listed in Table 11. The average plant available N levels available from several cool-season cover crops grown at high-elevations in Hawaii, and their respective nitrate release rates is provided by Pant et al., (2014). Table 12 provides the Nitrogen and Phosphorus tissue content of immature/green and mature/dry litter from several agroforestry species evaluated in Kauai.

Earlier research in North Carolina showed that residues with a lower C:N ratio and with lower levels of cellulose and hemicellulose resulted in faster Nitrogen release rates. For example with residues of the legumes hairy vetch and crimson clover, about 80% of the N was released by 8 weeks after residue desiccation. This compared to a 50% release rate of N after 8 weeks with rye residues, which had a higher C:N ratio of 36 vs 10 for the legumes, and a residue N content of 24 kg N/Ha vs 88 kg/Ha for the legumes (Wagger et al., 1998).

Research with residues from several legume and non-legume species in a coffee orchard on Brazil, showed that on average 32% of the Nitrogen was released during the first 15 days after residue placement. The amount of N release increased to about 83% of the initial levels found on the residues by 360 days after placement of the surface residues in the field (Matos et al., 2011). In the Pacific, an evaluation of nutrients released by several species used in shifting cultivation in Papua Guinea, determined that leaf residues of *Gliricidia* applied at a rate of about 5 MT/Ha, released about 80 kg/Ha of Nitrogen, with over 50% of the N released within the first six-months after application, and with about ⅔ of the total N released during the growth cycle of a subsequent sweetpotato crop (Hartemink and O'Sullivan, 2001)

Table 10. Uptake (percent recovery) of Nitrogen, mineralized from several crop residues, by a crop of Rye after 4 months of growth. The residues were mixed in the soil, prior to planting the rye crop. All the residues were applied, based on their N content, at a rate that would provide approx. 100 mg/N/ Kg of soil. Notice the higher N recovery rates from Pea and Cabbage, the more succulent residues, having a lower C:N ratio (adapted from Stockdale and Rees, 1995)

Residue	Nitrogen (%)	C:N ratio	N applied (mg/Kg of residue)	Percent Recovery (%)
Pea	4.13	7	85.5	33.9
Grass/clover turf	0.71	22	97.8	9.9
Cabbage	3.15	5	172.6	24.2
Straw	1.30	33	260.0	14.0
Composted farm-yard manure	2.95	11	100.3	10.9

Table 11. Nitrogen fixation of several agroforestry species, based on the literature (Adapted from Ståhl, 2005)

Species	Location	Plants/Ha	Time to harvest	N Fixation (kg N/Ha/Year)
Casuarina equisetifolia	Puerto Rico	10,000	12 month	43
Gliricidia sepium	Sri Lanka	5000	9 months	166
Faidherbia albida	Senegal	1600	12 months	65
Leucaena leucocephala	Nigeria	10,000	48 months	208-238
Sesbania sesban	Kenya	10,000	18 months	337-356

Table 12. The Nitrogen and Phosphorus tissue content of green and dry brown leaves of several species used as crop residues in Kauai, Hawaii (adapted from Constantinides,and Fownes, 1994)

Species	Nitrogen %	Nitrogen %	Phosphous (%)	Phosphous (%)
	Green leaves	Dry leaves/litter	Green leaves	Dry leaves/litter
Acacia	2.3	1.3	0.14	0.07
Calliandra	2.6	1.1	0.13	0.04
Cassia siamea	2.5	1.2	0.21	0.08
Gliricidia sepium	3.3	1.4	0.19	0.02
Inga edulis	2.5	1.6	0.26	0.12
Arachis hypogaea	2.5	NA	NA	0.15
Leucaena leucocephala	2.9	NA	NA	0.11
Sesbania sesban	3.4	NA	NA	0.22

Note, “All fresh samples were cut directly from plants, while most litter samples were intact brown leaves collected under trees” (Constantinides and Fownes, 1994))
NA= Not available

5.4. Phosphorus (P)

Organic materials added to the soil normally contain a range of 0.1 to 0.5% phosphorus (P). In soils with a high P fixation capacity, such as those often found in Hawaii, it is questioned whether P released from crop residues are readily fixed or sorbed by the high P fixing soils, or whether the P would become available for crop uptake. Early research conducted in high P fixing soils of Idaho, showed that crop residues with P tissue levels below 0.3%, such as sawdust, wheat straw, and corn stalks resulted in less P becoming available for crop uptake (with relative more P being sorbed or fixed by the soil), while residues with P tissue levels above 3% such as from alfalfa, barley, and beans, resulted in more soluble P available for crop uptake. However, even in cases when P from soil residues is fixed or sorbed by the soil, the research indicated that after about 5 months, some of this P also eventually is desorbed or released into the soil solution, eventually becoming available for crop uptake (Singh and Jones, 1976). Because the release of P from crop residues is dependant on the breakdown of residues by soil microbial activity, the periodic addition of organic matter to the soil, should affect the long-term decomposition of residues, and the rate of nutrient release for crop uptake.

A residue study was conducted in Argentina to evaluate the effect of hairy vetch and oat residue applications on the rate of Phosphorus release. The research showed that residues from hairy vetch released relatively more P to the soil, than oat residues. The residues were applied as dry biomass at rates of 1-4% of the soil weight. The baseline or original soil soluble P content in an experimental sites was about 20 ppm (parts per million). After 10 days of incubation with hairy vetch the levels of soluble P in the soil increased from 30 to 107 ppm ranging from the lowest to the highest rate of residues applied, respectively. By 120 days after incubation the levels of soluble P in the soil ranged from 30 to about 140 ppm, from the lowest to the highest rate of residues applied, respectively. In comparison, after 10 days of incubation with the oats residues the levels of soluble P in the soil increased from 25 to 37 ppm from the lowest to the highest rate of residues applied, respectively. By 120 days after incubation the levels of soluble P in the soil ranged from 33 to 57 ppm, from the lowest to the highest rate of oats residues applied, respectively (Vanzolini et al., 2017). This experiment illustrates the potential for crop residues to provide or supplement the P requirements of cash crops. It should be noted that the relatively higher release of P from the vetch residues can be attributed to the P content of the residue tissue contents, but also to the greater N levels in vetch, as the release of N may assist in the microbial decomposition of organic matter in the soil, resulting in the further release of P into the soil solution (Vanzolini et al., 2017). In subsistence or low-input cropping systems the use of residues has also been shown to increase soil fertility and the availability of soluble soil P levels (Warren et al., 2003).

5.5. Potassium

Among the nutrients, potassium (K) is readily leached, mineralized or released from residues because it is a non-structural component of plant parts. The rate of release of potassium from residues is normally related to the amount of rainfall or irrigation water. A crop nutrient residue study conducted in Papua Guinea with species typically used as part of shifting cultivation, determined that pretty much all of the available K was released from the surface residues six months after application compared to release rates of over 50% for Phosphorus and Nitrogen (Hartemink and O'Sullivan, 2001). Similar fast potassium release rates were reported from a coffee agroforestry study in Southern Ethiopia, using leaf crop residues from shade-tree species, including the non-legume *Cordia africana* Lam. and the legume *Albizia gummifera*, having K tissue values ranging from 12-38 ppm. After 16 weeks about 90% of the tissue K had been released from the plant residues, with faster release rates observed during the rainy season, and also with faster release rates observed with the legume *Albizia* compared to the non-legume *Cordia* (Teklay, 2007).

5.6. The Burning of Crop Residues and Nutrient Release

In many parts of the world farmers often burn crop residues, especially after harvest, as the field is prepared for the following crop in the rotation. The burning of residues helps to clear the field of litter and weeds, and allows for follow-up hand, animal, or mechanical tillage. The burning of residues also helps to kill disease or pests that may be harbored among the residues, and thus helps to reduce pest infestation levels prior to the planting of the following cash crop in the rotation. In some instances farmers also burn residues, with the goal of releasing nutrients for uptake by the following crop. Burning, however, results in the loss of about 25% of the Phosphorus, 20% of Potassium, and 5-60% of the sulfur content in crop residues (Gill, 2015).

Research was conducted in Australia under controlled conditions to simulate the effect of burning crop residues, and to evaluate its effect on nutrient availability (Gill, 2015). As part of the experiment several crop residues were burned at 550C. Over 95% of both Carbon and Nitrogen were lost during the burning process. A range of 80-98% of the total phosphorus in the residues was preserved, while the concentrations of potassium, sodium, calcium, magnesium, zinc and manganese actually increased during the burning process. The research also found that, when applied at similar rates of P, the P availability to plants in the soil was decreased with the use of burnt residues as compared to the use of unburnt residues (Gill, 2015).

6.0. The Effect of Residues on Water Conservation

Among the most easily quantifiable effects of surface residues is their improvement of Water Use Efficiency (WUE), and soil water relations, primarily by reduced evaporation, improved infiltration, and soil water holding capacity (Qin et al., 2015). These effects occur more readily, after the application of surface residues, when there is an active earthworm population in the soil, which assist in carbon cycling, moisture retention, and in water infiltration (Moldenhauer et al., 1995). Residues protect the soil from the energy of raindrops falling on the soil surface, preventing the dispersion of aggregates and seal development, which results in improved infiltration and in greater soil water storage. Residues also reduce the amount of runoff washing away, especially in sloped fields, which also provides more time for soil infiltration. Residue mulches also smother weed growth, which assists in water conservation, as weeds often compete with cash crops for the soil available water, especially under arid or rainfed conditions (Unger and Howell, 2000).

Early research with surface residues showed that each one percent increase in the soil organic matter content, from the application of surface residues, resulted in an almost 4% increase in the soil water holding capacity. The effects of surface residues on water soil relations are important because recognized water related variables that help to increase crop yields include increased water infiltration, decreased evaporation, increased water holding capacity, deeper rooting systems associated with crops grown under no-till farming, and the retention of surface residues, over time (Moldenhauer et al., 1995). For instance, research conducted in southeastern Nigeria showed that straw mulch applications at 2 MT/Ha improved soil-water sorptivity, transmissivity, and infiltration-rate compared to the no-mulch controls (Mbagwu, 1991). Early research evaluating the effect of residue mulch application rates on water conservation showed that soil water storage to a 1.8 m depth increased from 72 and 116 to 147 mm, with residue application rates of 0, 4, and 12 MT/Ha, respectively. The respective levels of Water Use Efficiency (WUE) were 0.56, 0.84, and 1.15 Kg/m3, with the mulch application rates of 0, 4, and 12 MT/Ha, respectively (Unger and Howell, 2000).

Crop residues help to reduce evaporation losses, especially under windy conditions, as residues help to moderate both wind speed and high temperatures at the soil surface. Experiments conducted in Colorado indicated that water evaporation losses were 1.5 times greater on bare soils, compared to soils that had received about 3 MT/Ha of wheat straw residues (Croissant et al., 1994).

7.0. Residue applications and Pest Interactions

7.1. Crop Residues and Pest Management strategies

Because crop residues play an important role in the soil in terms of biophysical interactions, soil quality, fertility, microbial and fauna biodiversity, and water relations, they are likely to play both a direct and indirect role in the pest population dynamics on the farm. Above ground, residues provide a physical barrier, which alters the microhabitat in terms of light interception, wind speed, temperature and humidity. As such, residues may serve as a source of nourishment and refuge for beneficial organisms. The same conditions, however may also promote the activity of pests and diseases. Farmers need to be aware of the potential risks and benefits and make decisions about the type of residues to use, timing of applications (say, rainy vs. dry season), based on the particular crop sequence and field conditions- with the goal of promoting a diverse fauna population and to minimize the likelihood of pest outbreaks on the farm.

Early field surveys indicated that crops residues from several sources increased the population of micro-fauna (Tian et al., 1993), which promoted biological activity and nutrient cycling in the agroecosystem. A positive correlation was also identified between the amount and composition of crop residues with the activity and diversity of decomposer and predator organisms in the soil (Hättenschwiler et al., 2005).

7.2. Diseases management with Crops Residues

Crop residues may have positive, neutral, or adverse effects on the incidence of diseases on cash crops. A literature review on the effect of plant residues on incidence of disease found that 45% of the reports showed suppressive effects on diseases, while 28% of the reports showed enhanced disease development. Diseases that were most effectively controlled with the use of organic amendments included *Verticillium*, *Fusarium*, *Sclerotinia,* and *Phytophthora* spp. (Table 13). The literature showed that the use of crop residues was effective or very effective for the suppression of *Rhizoctonia*, *Pythium*, *Fusarium*, *Phytophthora*, *Verticillium*, and for *Thielaviopsis*. Over 50% of the studies evaluated indicated that increased application rates of crop residues and other organic amendments resulted in more effective disease suppression (Bonanomi et al., 2007).

Early research indicated that a high Carbon to Nitrogen (C:N) ratio resulted in a lower disease incidence, perhaps by reducing the availability of Nitrogen for pathogen growth (Bonanomi et al., 2007). For example additions of glucose or cellulose, or of residues high in C such as mature barley straw, wheat straw, corn stover, and pine shavings, applied to increase the soil C:N ratio, resulted in a lower incidence of Fusarium root rot in bean (Maurer and Baker, 1965; Papavizas et al., 1968). Adding Nitrogen, neutralized or nullified the effect of the high Carbon residues, to control Fusarium in bean (Adams et al., 1968a).

Extracts from the degradation of crop residues may help to reduce disease incidence on cash crops. For instance, early work showed that Brassica residues were effective in reducing the incidence of *Aphanomyces* Root Rot on Peas, with the disease suppression lasting almost four months (Papavizas, 1966). Other research indicated that when Brassica leaves and stems were applied at a rate of 0.5% of the soil dry weight, that there was a reduction in the disease severity index and oospore number (Chan and Close, 1987). Reduction of disease incidence is important with soil borne-diseases, such as *Aphanomyces* Root Rot, which may persist over several years in the soil. For instance, a high disease incidence of *Aphanomyces* was still observed in soil samples of commercial fields that had been without peas, the host crop, for a period of 6-8 years (Temp and Hagedorn, 1967). Residues from the previous crops, however, may have an effect on the subsequent levels of disease incidence. With respect to *Aphanomyces* Root Rot in peas, higher levels of *Aphanomyces* were observed in the soil following corn, grains, and vegetables, while lower disease levels were observed following the planting of forage crops (Temp and Hagedorn, 1967).

Subsequent research showed that volatiles emitted from the decomposition of cabbage residues during solarization, such as isothyocianates and aldehydes, inhibited the growth of fungal disease organisms such as *Pythium* and *Sclerotium*. Control of these plant diseases by the volatile compounds may have been caused by a combination of direct toxic effects on the pathogens, along with a stimulation of beneficial antagonistic organisms by the volatile compounds (Gamliel and Stapleton, 1993). In California, residues from recently harvested broccoli, applied at a rate of about 50 tons/Ha, and allowed to decompose for 3 weeks, as part of a normal fallow period between crops, was effective for management of verticillium wilt in cauliflower, over two years of field trials (Koike and Subarao, 2000).

7.3. Predisposition to disease with crop Residues

The extracts of crop residues as they decompose in the soil, can predispose some crops to increased disease incidence (Table 14). A review of the literature showed several reports where the use of crop residues enhanced disease development for *Rhizoctonia*, *Pythium*, *Fusarium*, *Phytophthora*, and *Thielaviopsis* (Bonanomi et al., 2007). For example, early research showed that cotton plants treated with extracts from the decomposition of barley residues increased the susceptibility to *Thielaviopsis* Root Rot (Table 14). These residue extracts in some cases are also able to break down a crop's resistance to a soil disease or to avirulent or mild strains of the pathogen (Linderman and Toussoun, 1968). In some instances phytotoxic effects of residue extracts on crop growth, may weaken the plants, and thus predispose them to attack by pathogens (Carley and Watson, 1967). While this would not be desirable for the production of cash crops, the targeted use of residue extracts may be a possible technique for the biological control of weeds, by making them more susceptible to particular soil-borne diseases.

Residues should be used more cautiously in fields with a history of *Pythium*, *Rhizoctonia*, and *Sclerotium*. *Pythium* and *Rhizoctonia* often use organic matter sources as nutrient substrates. Volatiles from crop residues have also been shown to stimulate germination of sclerotia, possibly leading to an increase of disease incidence (Bonanomi et al., 2007). Factors that will affect potential risks of increased disease development include field history, current field conditions, the presence of antagonistic organisms in the soil, the type of residues, as well as the subsequent crop in the rotation.

Table 13. Reduce disease incidence observed on cash crops from exposure to extracts or decomposition of crop residues.

Reduced Disease Incidence	Crop Residue Extracts	Citation
Aphanomyces Root Rot of Peas	Radish, Cabbage, Brussel Sprouts, Brassica	Papavizas, 1966; Chan and Close, 1987
Macrophomina root rot of cotton, Increased population of antagonist organisms	alfalfa meal	Ghaffar et al., 1969
Pink Root in onion, *Pyrenochaeta*, reduced incidence	Young soybean tissues, sweet clover	Latham and Watson, 1967
Bean root rots: *Rhizoctonia*, *Thielaviopsis*, and *Fusarium*	Oat straw at high C:N ratios; also: Cellulose, chitin, barley straw, cabbage leaves and stems, and especially corn stover and alfalfa hay	Papavizas, 1968; Papavizas et al., 1968; Snyder et al., 1959

Fusarium root rot, beans	Spent coffee grounds at 0.5-1% (w/w of soil), beans planted 1-2 weeks after application	Adams et al., 1968b
Verticillium alboatrum	Alfalfa and oat residues, apparently affect propagule survival	Green and Papavizas, 1968
Verticillium wilt of Cauliflower	Broccoli residues	Koike and Subarao, 2000
Phytophthora Root Rot of Avocado (more effective control in some soils than others)	Alfalfa meal by promoting beneficial microbial activity	Gilpatrick, 1969
Bacteria, *Xanthomonas* spp.	Substance from caulifiower seed, growth inhibition	Malekzadeh, 1966

Table 14. Increased disease incidence observed on cash crops from exposure to extracts or decomposition of crop residues.

Increased Disease Observed	Crop Residue Extracts	Citation
Thielaviopsis Root Rot in cotton, bean and tobacco	Barley and other crop residues	Linderman and Toussoun, 1968
Root rot in bean, caused by *Fusarium*, *Rhizoctonia*, *Thieiaviopsis*	Green Barley hay residues	Snyder et al., 1959

7.4. Management of Weeds with Crop Residues

The effects of decomposing organic amendments on the growth of plants was studied extensively during the first half of the last century. This research indicated that extracts of plant residues, such as from barley, could be phytotoxic or affect the growth of plants (Toussoun et al., 1968). Plant derived chemicals that have allelopathic potential include phenolic acids, flavonoids. terpenoids, alkaloids and quinones, and most plant species may contain some level of allelopathic activity (Chung et al., 2003).

Extracts from crop residues, as they decompose in the soil, can be phytotoxic or allelopathic to the subsequent crops in the field (Table 15; Linderman and Toussoun, 1968). For example, early research, surveying extracts from several plant species showed that extracts from onions reduced the growth of clover, radish and wheat (Carley and Watson, 1967). Research in

Australia evaluated the potential allelopathic effect of mulch residues from subterranean clover (*Trifolium subterraneum*), annual ryegrass (*Lolium rigidum*), and alfalfa on the seedling growth of lettuce, broccoli, and tomato. Both the subterranean clover and annual ryegrass showed allelopathic effects, but alfalfa did not reduce the growth of any of the crops. The study showed that leacheates from the cover crops likely caused the reduced growth of the seedlings and the allelopathic effects lasted for 8 weeks or longer, under field conditions (Stirzaker and Bunn, 1996).

The allelopathic effect of residues on plants can be very complex, as indicated by early research (Stirzaker and Bunn, 1996). Factors that affect the phytotoxicity of plant residues includes plant species, part, and age; the concentration of the leachates in the soil can have differential effects, inhibiting plant growth at high concentrations, but stimulating growth at lower concentrations; and, the same leachate may inhibit growth in some species, but stimulate growth in other species. In general roots are more affected than shoots by allelopathic compounds (Stirzaker and Bunn, 1996).

Residues are also used as a mulch, to provide a physical barrier to smother weed growth (Valenzuela, 2011). In California, an experiment was conducted to evaluate the effect of sudangrass (*Sorghum X drumondii*) residues in combination with solarization for the management of weeds and diseases in strawberry. The use of sudangrass residues used as a mulch, at a rate of about 10,000 Kg/Ha, resulted in an initial 80-90% improved weed control compared to the unmulched controls. However, as sudangrass had been planted as a cover crop prior to the planting of strawberries, there were problems of sudangrass re-growth in the field. Overall, a combination of solarization and mulch residues resulted in the best levels of weed control, and the solarization also prevented the re-growth of sudangrass (Jacobs, 2019).

Residues are also used as a weed control strategy under no-till or conservation farming. However, under some conditions of relative little ground cover, residues may not be an effective barrier to manage weeds in the field. The relative low levels of corn residues left in the field as part of alternative tillage systems evaluated in Zimbwawe as well as relative poor crop growth, resulted in weed infestations which still required manual labor for weeding. The corn residues in the field, in the form of stalks, also made it more difficult to hand weed with a hoe. In addition, perennial weed species (*Richardia*, and Bermuda grass, *Cynodon dactylon*) increasingly became a problem in the no-till and relative low residue systems (Vogel, 1994). The experience from Zimbwawe highlights the need for local applied research to fine-tune the crop selection and residue management practices, to the local agro-social and environmental conditions.

Table 15. Some examples of the allelopathic effect of crop residues

Allelopathic Effects	Crop Residues	Citation
Phytotoxic on other plant species	Barley	Toussoun, 1968
Prevents germination of lettuce	Celery, compound psoralen	Shilling et al., 1992

Reduced seedling growth of lettuce, broccoli and tomato	Both subterranean clover, Trifolium; and annual ryegrass, Lolium rigidum	Stirzaker and Bunn, 1996
Emergence of snap beans reduced by 64%	Canola (rape) residues, Brassica napus L. ssp. oleifera	Smith, 2000
Barnyard (Echinochloa) grass control and other species	Rice, some accessions	Chung et al., 2003; Khang et al., 2016
Control, several weed species	Buckwheat	Kumar et al., 2009; Sangeetha and Baskar, 2015
Control, several weed species	Rye	Sangeetha and Baskar, 2015

7.5. Residues effects on Nematode pests

Crop residues may be used to manage nematode populations in the soil. Early research showed that oat straw residues, at particle sizes of ⅛ inch, and applied at a rate of 1% by weight of soil, was effective for the control of the root knot nematode (*Meloidogyne*) in tomato. Environmental conditions, such as a lower soil pH, temperature, and soil moisture were additional variables that had an impact on nematode suppression (Johnson, 1962). Plant species with reported nematicidal activity when used as green manures or plant residues include those from the Brassica or Cruciferae family, by either increasing the activity of beneficial organisms, or by possessing nematicidal or 'biofumigant' properties from the activity of glucosinolates. Considerable differences exist among Brassica species, with respect to their glucosinolate content. Other plant species with nematicidal activities, as residues, include several Marigold (*Tagetes*) species, *Ruta graveolens* (Rutaceae family), rye, sunnhemp, and several weed species (Alam, 1986; Wang and McSorley, 2012; D'Addabbo et al., 2014; Renco et al., 2014).

Some tannins, which are secondary metabolites found in leaves and plant residues, have been reported to have nematicidal activity on several nematode species (Renco et al., 2014). Research indicates that other secondary metabolites extracted from plant residues, such as alkaloids, saponins, monoterpenoids, pentacyclic, triterpenoid, triglycerides, sesquiterpenes, steroids, diterpenes, flavonoid and glucosinolates may also have nematicidal properties, or repellant effects on nematodes. Research indicates that secondary metabolites may act as attractants, repellants, reduce hatch levels, induce paralysis, and even cause nematode death.

The potential effects of plant extracts on beneficial nematode populations in the soil, however, needs to be considered as well. Extracts of plant residues that have shown nematicidal activity includes extracts from *Azadirachta indica* (neem), *Chrysanthemum*, *Euphorbia*, *Nicotiana tabacum* (tobacco), *Artemisia*, *Foeniculum vulgare* (Florence fennel), *Origanum*, *Mentha*, *Eucalyptus* spp, and leaves of *Citrus sinensis* (orange). Additional research has found that volatiles from several species, such as from marigold or *Brassica* spp., as well as water extracts from plant residues, such as from leaves of neem and lemongrass, have also shown nematicidal activities (D'Addabbo et al., 2014; Renco et al., 2014).

8.0. Conclusions

Crop Residues may provide several key ecological services on the farm with respect to building the soil, soil quality and fertility, and with respect to several biological processes, including promoting soil biodiversity, nutrient cycling, and biological control of pests below-and above ground. However, the use of crop residues also present several challenges, including the logistics of their management and application, coordinating their management with the timing of other agricultural operations, as well as having several potential adverse effects on the production of cash crops such as excessive moisture during wet periods, potential allelopathic effects on the cash crop, harboring disease and arthropod pests causing potential pest outbreaks, as well as the additional time and labor required for their management.

The decision making process concerning the use of crop residues is also quite complex, if locally-based research has not been conducted to provide specific recommendations about their use. Some of the questions that need to be answered in order to make informed and timely decisions with respect to the use of crop residues include the species and particular cultivars of cover crops or hedge-row species to use, guidelines for the use of species mixtures (such as legume-cereal combinations), the timing of application, the appropriate species to use based on particular needs (such as moisture management, weed control, or to contribute nutrients to a cash crop), and the performance of crop residues during the different times of the year. While considerable research has been conducted over the past 120 years with crop residues, local-based research is still needed to adapt production techniques that have been developed in other locations.

Overall the use of crop residues offer the potential to reduce the use of external inputs on the farm, by reducing the reliance on purchased organic or synthetic fertilizers, pesticides, and amendments. The future use of residues in places like Hawaii, however, will be affected by the demand for alternative uses such as for military bio-jet fuels (Zhang et al., 2015; Pawloski et al., 2017). On the farm, residues are best used by following the concepts of agroecology which place a focus on the promotion of key ecological concepts and processes such as internal nutrient cycling, fauna and vegetational diversity, and biological control, as well as on the concept of social and rural self-sufficiency and economic well-being (Rosset and Altieri, 2017).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

9.0. References

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Table Captions

Table 1. Potential benefits provided by Crop Residues

Table 2. Potential problems with the use of crop residues

Table 3. Percent of lignin in plant residues (dry weight) of several plant species (also see Matos et al., 2011)

Table 4. The Carbon to Nitrogen (C:N) ratio from residues of several crop and agroforestry species, as reported in the literature.

Table 5. Percent Nitrogen (N) tissue content of several agroforestry species. The samples from Oglesby and Fownes, were part of an alley-crop, agroforestry study conducted in Kauai.

Table 6. Percent degradation and chemical constituents of leguminous cover crops mowed at an immature stage and at a ripening stage. Percent decay of residues was determined at 90 days after incubation, to determine levels of residue decomposition from either young (immature) or older (more mature) plant residues (adapted from Köpke, 1996).

Table 7. Early mulching recommendations for home-gardens in Hawaii (McCall and Nakagawa. 1980ab).

Table 8. The fate of Carbon (decomposition and incorporation into soil organic matter) when plant residues are applied either as a surface residue (mulch) or incorporated into the soil. This data are based on research from France with rape residues under controlled environmental conditions during a 9 week period of evaluation (adapted from FAO/IAEA, 2008).

Table 9. The positive impacts contributed by surface residues, to reduce erosion rates, (Moldenhauer et al., 1995; Zachmann and Linden, 1989)

Table 10. Uptake (percent recovery) of Nitrogen, mineralized from several crop residues, by a crop of Rye after 4 months of growth. The residues were mixed in the soil, prior to planting the rye crop. All the residues were applied, based on their N content, at a rate that would provide approx. 100 mg/N/ Kg of soil. Notice the higher N recovery rates from Pea and Cabbage, the more succulent residues, having a lower C:N ratio (adapted from Stockdale and Rees, 1995)

Table 11. Nitrogen fixation of several agroforestry species, based on the literature (Adapted from Ståhl, 2005)

Table 12. The Nitrogen and Phosphorus tissue content of green and dry brown leaves of several species used as crop residues in Kauai, Hawaii (adapted from Constantinides,and Fownes, 1994)

Table 13. Reduced disease incidence observed on cash crops from exposure to extracts or decomposition of crop residues.

Table 14. Increased disease incidence observed on cash crops from exposure to extracts or decomposition of crop residues.

Table 15. Some examples of the allelopathic effect of crop residues

Figures Captions

Figure 1. Straw mulch evaluation for the production of bulb onions at the UH Waimanalo Experiment Station. Supplemental Nitrogen amendments may be necessary because of the relative high C:N ratio of the straw mulch.
db sl-06716.jpg

Figure 2. The use of crop residues and sorghum/ornamental insectary borders for the production of eggplant at the organic plots of the UH Waimanalo Experiment Station.
MOA db-14070.JPG

Figure 3. The placement of woody residues within rows at an organic orchard in Kauai.
2007-01-19 15.56.20.jpg

Figure 4. View of residues from Rhodes grass (*Chloris gayana*) mowed 3 months after planting at the Organic Plots of the Waimanalo Experiment Station, with weed infestation levels of 10%, on an area basis (compared to 3, 13, 25, and 74% infestation levels for treatments with sorghum, cowpea, mustard, and bare plots, respectively).
db sl-07182.jpg

Figure 5. View of residues from cowpea mowed 3 months after planting at the Organic Plots of the Waimanalo Experiment Station, with weed infestation levels of 13%, on an area basis (compared to 74% infestation for bare plots).
db sl-07177.jpg

Figure 6. View of residues from 'Dwarf Essex' mustard mowed 3 months after planting at the Organic Plots of the Waimanalo Experiment Station, with weed infestation levels of 25%, on an area basis (compared to 74% infestation of bare plots).
db sl-07175.jpg

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