

Food-Producing Agroforestry Landscapes
of the Pacific (Series)

Enhancing soil function
and plant health with
locally available resources

By Ted Radovich, Archana Pant, Amjad Ahmad,
Craig Elevitch, and Nguyen Hue



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INTRODUCTION

The wholesale cost of commercial fertilizers more than tripled between 2006 and 2008 in the U.S., and considering increasing transportation costs from the mainland U.S., costs to growers are rising even faster in Hawai'i and elsewhere in the Pacific. Prices are only expected to climb over time, leading to increased demand for less expensive, locally available materials that can be used as fertilizers. Keeping farmers competitive in the marketplace while improving food security in the Pacific Islands requires that cost effective, stable sources of local fertilizer be available to growers, and that growers understand how to best use these resources.

Proper ecological function of soil is critical to support optimal plant growth and quality. Sustained health of the soil relies on carbon rich amendments that will feed the biological processes that are the foundation of a healthy soil. Short-term needs must also be met with fertilizers that can rapidly become available to plants so that nutrients are available in synchrony with plant needs. Fortunately, many of the locally available resources for enhancing soils can serve both long and short term crop nutrient needs better than many imported fertilizers when used properly.

This chapter focuses on the use of locally available resources to enhance soil function and plant health in the short and long term. The emphasis is on a description of the inputs, pros and cons of use, specific conditions in Hawai'i and recommendations for food producers. This is intended to be a concise, practical guide for local food producers, rather than a comprehensive treatment of each topic. Recommendations for further reading on specific topics are provided where relevant.

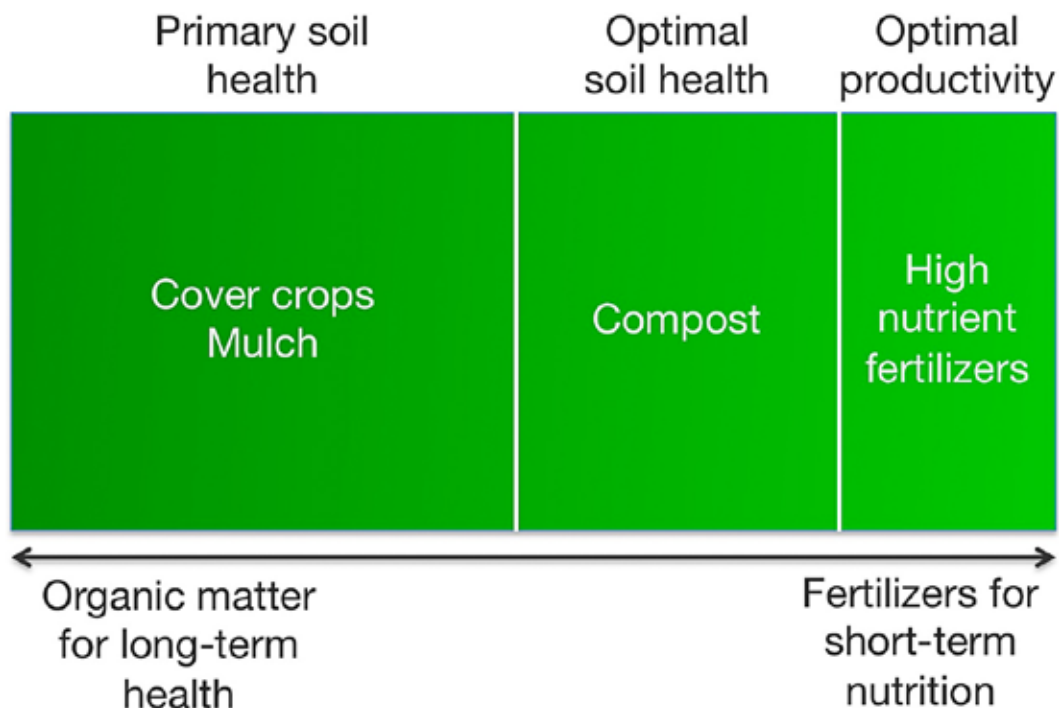


Figure 1. A variety of organic materials can be used to fulfill long- and short-term nutrient needs, while also building long-term soil fertility.

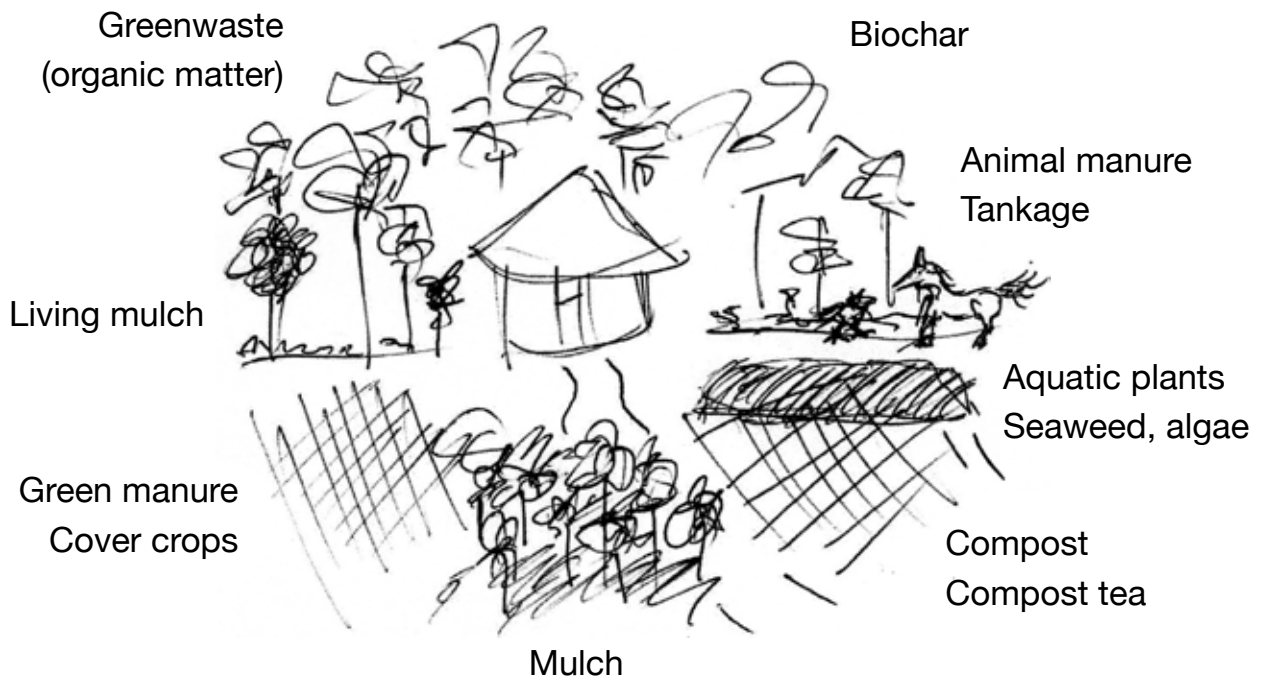


Figure 2. The range of on-site and locally available resources that can enhance soil health and productivity is extensive.

COVER CROPS

Plants that are grown to feed the soil (rather than people or animals) are generally called “cover crops,” and are also referred to as “green manures” and “living mulch” depending on their primary purpose. Cover crops are often planted as a rotation between food crops to break pest cycles, conserve topsoil, add organic matter, and suppress weeds. Cover crops are preferable to a weedy fallow because they typically produce more biomass than weeds, are easier to control, and do not contribute to the weed seed bank. Long term soil fertility is primarily the goal of cover crops, rather than the short term, direct nutrient contribution for an immediately following crop (except for green manures). See Appendix 2 for details on specific cover crops.

Green manure

Green manures are cover crops that are grown specifically to increase the nutrient availability for a subsequent crop. Legumes are the most common plant family used for green manure because of their ability to fix atmospheric nitrogen. Other species grown as green manures include buckwheat and several grasses. Sunn hemp and perennial peanut are the most common green manure species in Hawai'i vegetable and fruit tree systems, respectively (perennial peanut also serves as a living mulch in orchards). Interest has also recently been renewed in lablab as a green manure in both annual and perennial systems. Other legume species utilized for green manure include cowpea, hairy vetch, sweet clover, and alfalfa. Special attention to management must be employed to ensure that nutrient benefits are realized in the near term. This

Table 1: On-farm organic matter sources

Practice	Example species	Life cycle duration
Green manure <i>Fast growing field crops</i>	Sunn hemp, oat, Sudan grass, buckwheat, velvet bean	6–20 weeks, depending on species and management practices
Living mulch <i>Slow to medium growing ground covers</i>	Perennial peanut, <i>Desmodium heterophyllum</i> , glycine	10+ years
Mulch banks <i>Fast growing trees</i>	<i>Leucaena*</i> , <i>Gliricidia</i> , <i>Cajanus</i> , <i>Acacia**</i> , <i>Sesbania*</i> and <i>Calliandra</i>	3–60 years, depending on species

* Likely to be invasive in Hawai'i and on other Pacific Islands as determined by the process, which is based on published sources describing species biology and behavior in Hawai'i and/or elsewhere.

** Documented to cause significant ecological or economic harm in Hawai'i, as determined from published information on the species' current impacts in Hawai'i.

includes environmental adaptation. For example, vetch, sweet clover and alfalfa perform better at higher elevations (above 460 m [1,500 ft]), while cowpea is more appropriate for lower elevations. For additional management suggestions, see the inset “General recommendations for the management of legumes for maximum N contribution” below.

Invasive species concerns

Many rapidly growing cover crop candidate species have potential to become a nuisance or cause economic or ecological harm. Weed risk assessments for many cover crop, green manure and living mulch species may be found in “Weed Risk Assessments for Hawai'i and Pacific Islands” (Daehler, no date). Weed risk assessment can be a valuable tool for minimizing invasive plant problems, but should not be used as primary justification for removing or unconditionally excluding trees or other plants from agricultural systems. A high risk designation is an indication of risks in some environments, but should not be interpreted to mean “do not plant under any circumstances.” The potential for invasiveness can be reduced by mowing or otherwise killing cover crop before seeding.

Living mulch

Living mulch is a term used to describe cover crops that are grown concurrently with food crops. Like other cover crops, the primary short-term benefits of living mulches to food crops include breaking pest cycles, erosion control, and displacing weeds. Additional benefits from living mulches compared to other covers include:

1. A reduction of the land area taken out of production for a given period of time,
2. A physical barrier against pests (e.g., taller living mulches can intercept wind blown pests),
3. Compatibility with perennial systems where intensive cover management is not feasible or desired.

Living mulches may also function as green manures in some cases, where old biomass (leaves, root, nodules etc.) dies or is cut back, decomposes and mineralizes to contribute nutrients to the concurrent crop.

Cover crops contribute a relatively high amount of biologically active carbon when incorporated. The additional ecological benefits they provide make them preferable in many ways to compost. Transportation of cover crop seed over long distances is also less costly than compost. Costs associated with lost production area and other management costs may be offset by cost-share programs offered by USDA NRCS.



Figure 3. Vetch living mulch in papaya orchard, Waimānalo Research Station, O'ahu. Note wood chip mulch around trees.



Figure 4. Lablab cover crop, Waimānalo Research Station, O'ahu.

Nitrogen contribution by green manures can amount to 39–500 kg/ha (40–580 lb/acre) per year depending on species and environmental conditions (NifTAL Center 2000). Legumes are not the only covers that can be used to improve nitrogen availability. Buckwheat alone or in combination with other species reportedly improves P and K availability after incorporation (CTAHR 2012). Oats, sorghum × Sudan grass hybrids and other grasses are used to prevent N loss from the system after incorporation of legumes or manures by scavenging excess plant available nitrogen in the soil if no crop is to be grown.

Despite NRCS cost-share programs and other support, cover crop cost may be high in the short term. Irrigation water costs can be significant

Nitrogen fixing legumes for cover crops

General recommendations for the management of legumes for maximum N contribution and benefit to soil health include:

- Soil pH should be above 6.0.
- Phosphorous requirement of N-fixing plants is higher than non-fixing plants.
- Nitrogen fixation is improved by moderate amounts (e.g., 56 kg/ha [50 lb/acre]) of available nitrogen early in growth, but will be inhibited by excessive N (>112 kg/ha [>100 lb/acre]).
- Keep legume living mulches away from the base of plants because legumes will compete for nitrogen.
- Even though tropical legumes such as sunn hemp, perennial peanut, cowpea and pigeon pea are usually compatible with local soil rhizobia, inoculation at the time of planting is recommended, especially in highly weathered and nutrient-poor soils.
- Other legumes like common bean and soybean will typically not fix N with locally present rhizobia and require inoculation with compatible bacteria in order to fix N.
- Generally, legumes are best turned under or mowed at 50% flowering when their readily available N is highest. Also, many legumes become fibrous as they mature making them harder to cut and incorporate.
- Harvesting beans from legumes removes nitrogen from the system.
- Incorporate green manures into the soil for maximum N contribution. Chopping residue to fine pieces, and warm, moist soil improves mineralization. For recommendations for non-incorporated green manure, see “Mulching” section below.
- It is estimated that 50–75% of the total nitrogen in legume green manures will be plant available within 2 months of incorporation if the above recommendations are followed.

(\$125–250/ha/month [\$50–100/acre/month]) and therefore may limit cover crop use to periods of adequate rainfall. Seed costs can also be high, e.g., \$300/ha (\$120/acre) for sunn hemp and \$1500/ha (\$600/acre) for perennial peanut. With the exception of sunn hemp, locally produced cover crop seed is not currently commercially available. Also, legume green manures may require fairly intensive management to maximize the potential for nitrogen contribution to a subsequent crop. These costs may be offset in the long term by improved soil function including elevated nutrient availability, increased water holding capacity, reduced disease incidence, etc. Unfortunately, these potential long term benefits are difficult to measure and often not considered when calculating returns.

MULCHING

Mulching uses uncomposted plant residues to suppress weeds and conserve moisture. Grasses, leaves, soft woody prunings, and wood chips are the primary materials used. Mulching is a time-honored practice that, like cover cropping, provides a host of benefits to soil and plant health beyond the addition of nutrients. Used as mulch, uncomposted organic matter can:

1. Protect the biologically active topsoil from temperature and moisture extremes,
2. Improve water use efficiency by reducing evaporation,
3. Reduce competition from weeds,
4. Reduce soil loss and compaction from rain,



Figure 5 (top left): Zucchini growing in sunn hemp living mulch, Twinbridge Farms, O’ahu. Figure 6 (top right): Mixed oats, sunn hemp and lablab cover crop at the Waimānalo Research Station, O’ahu. Figure 7 (bottom left): Sunn hemp and Sudan grass cover crop plant to restore long term soil fertility in a lo’i at Chris Kobayashi and Dimi Rivera Farm, Kaua’i. Figure 8 (bottom right): Buckwheat cover crop at Kaua’i Authentic Gardens. The buckwheat is allowed to flower and set seed for chickens to eat, followed by vegetable cropping.

5. Make it easier to harvest after a rain in clay soils,
6. Protect vegetables from soil contamination, and,
7. Add organic matter as it decomposes.

The larger the particle size, the longer a mulch persists. Coarse mulch of 2.5–5 cm (1–2 in) particle size such as fresh wood chips from a commercial wood chipper is commonly used to mulch fruit trees and other perennial crops. Finely milled woody mulch (e.g., sawdust) will degrade relatively quickly and actively compete for nitrogen. Weed-free straw



Figure 9. Pruning and chipping *Leucaena* trees for mulch at the Waimānalo Research Station, O‘ahu.



Figure 10. Alley cropping hedgerows of *Calliandra calothyrsus* on this Hōlualoa farm provide nutrient rich mulch every time they are pruned, usually 2–3 times per year.

Alley cropping and mulch banks

Leguminous nitrogen fixing trees (NFTs) may be interplanted with crops in a strategy called alley cropping. Candidate species include *Leucaena*, *Gliricidia*, *Acacia*, *Sesbania* and *Calliandra*, the selection of which should be based on environmental conditions, tree characteristics, and invasiveness potential. In alley cropping, hedgerows of trees are pruned periodically, and these materials may be incorporated into the soil or used as mulch. When incorporating into soil, care must be taken to avoid using excessive quantities of woody material. NFTs may also be similarly used in boundaries, hedges or block plantings throughout the farm as a form of mulch bank. Woody matter is more commonly used on the soil surface as mulch. For more information on integrating NFTs into farm systems see Elevitch and Wilkinson (1999).

and grass are often used for vegetable beds. The mulch layer should be applied at a thickness of 5–10 cm (2–4 in). The coarser the mulch, the thicker it should be applied to exclude light and maximize weed suppression. Excessive mulch around crops may result in damage due to reduced aeration and nutrient availability, excessive moisture, and increased pest build up, such as slugs and snails.

Purchasing and/or transporting mulch may be expensive, so trees are often grown on-site as a source of mulch that may be chipped (Figure 9) or used as mulch without any processing (Figure 10). Mulching with trimmings from leguminous trees, as is done with alley cropping (see alley cropping inset above), can be a valuable strategy to provide ecological services above ground, while also supplying some plant nutrients in the short term. For detailed case studies of alley cropping in the tropics see e.g., Elevitch and Wilkinson 1999; Elevitch et al. 1999; Evensen et al. 1995; and Rosencrance 1992.

The following formula can be used to determine how much mulch is needed for a specific area:

Metric units: Specific area to cover (m²) × depth of mulch desired (cm) × 0.1 = cubic meters of mulch required

For example, to cover an area of 10 square meters 10 cm deep:

$$10 \text{ m}^2 \times 10 \text{ cm} \times 0.1 = 1 \text{ cubic meter}$$

Imperial units: Specific area to cover (ft²) × depth of mulch desired (in) × 0.0031 = cubic yards of mulch required

For example, to cover an area of 100 square feet with 3 inches of mulch:

$$100 \text{ ft}^2 \times 3 \text{ inches mulch} \times 0.0031 = 0.93 \text{ yd}^3 \text{ of mulch.}$$

MANURE

Manure is most frequently used by growers who also raise animals, or by food producers who have neighbors who raise or board poultry or livestock. Generally, raw manure is composted before application. If

composting is not feasible, uncomposted manures are usually applied 90–120 days prior to harvest of food crops for food safety.

Manures are such an important source of plant nutrients and organic matter for plant and soil health, that the term “manuring” has become synonymous with fertilization. Nutrient concentration varies widely with manure type (Appendix 1) and the availability of N declines as manures age or are composted. Nitrogen from poultry manures (non-composted) is more quickly available than N in manure from cow, horses, and sheep. This is due to the relatively high levels of uric acid, which is readily decomposable in chicken manure, whereas the lignin and cellulose in cattle and horse manure break down more slowly. Bedding or litter lowers N content by dilution, and may slow the availability of nitrogen by increasing the ratio of carbon to nitrogen. Wet manure undergoes significant loss of N as ammonia (NH_3) when exposed to air in a process



Figure 11 (top left): Locally produced compost and mulch form the bulk of this rooftop garden run by Sweet Home Waimānalo restaurant, O‘ahu. **Figure 12 (top right):** Wood chip mulch laid prior to the planting of rooted ‘awa cuttings, Moloka‘i. **Figure 13 (bottom left):** Kukui stem mulch decomposing in lo‘i, Ulupo, O‘ahu. **Figure 14 (bottom right):** A simple mulch of palm fronds used to rest garden beds and keep them moist and cool at Joe Krimm Farm, Hōnaunau.

Manure: guidelines for composting (NOP rule 205.203(c)(1))

For food safety reasons, raw animal manure must be composted or heat processed unless it is: (i) applied to land used for a crop not intended for human consumption; (ii) incorporated into the soil not less than 120 days prior to the harvest of a product whose edible portion has direct contact with the soil surface or soil particles; or (iii) incorporated into the soil not less than 90 days prior to the harvest of a product whose edible portion does not have direct contact with the soil surface or soil particles.

Manure should be composted through a process that establishes an initial C:N ratio of between 25:1 and 40:1 and maintains a temperature of between 131°F and 170°F for 3 days using an in-vessel or static aerated pile system, or maintains a temperature of between 131°F and 170°F for 15 days, during which period the composting materials must be turned a minimum of five times in a windrow system.

Manure products processed so that all portions of the product, without causing combustion, reach a minimum temperature of either 150°F (66°C) for at least one hour or 165°F (74°C), and are dried to a maximum moisture level of 12%; or an equivalent heating and drying process could be used. Processed manure may be used as a supplement to a soil-building program without a specific interval between application and harvest.

Composted or processed manure products must not contain more than 1×10^3 (1,000) MPN fecal coliform per gram of processed manure sampled and must not contain more than 3 MPN Salmonella per 4 grams of processed manure sample.

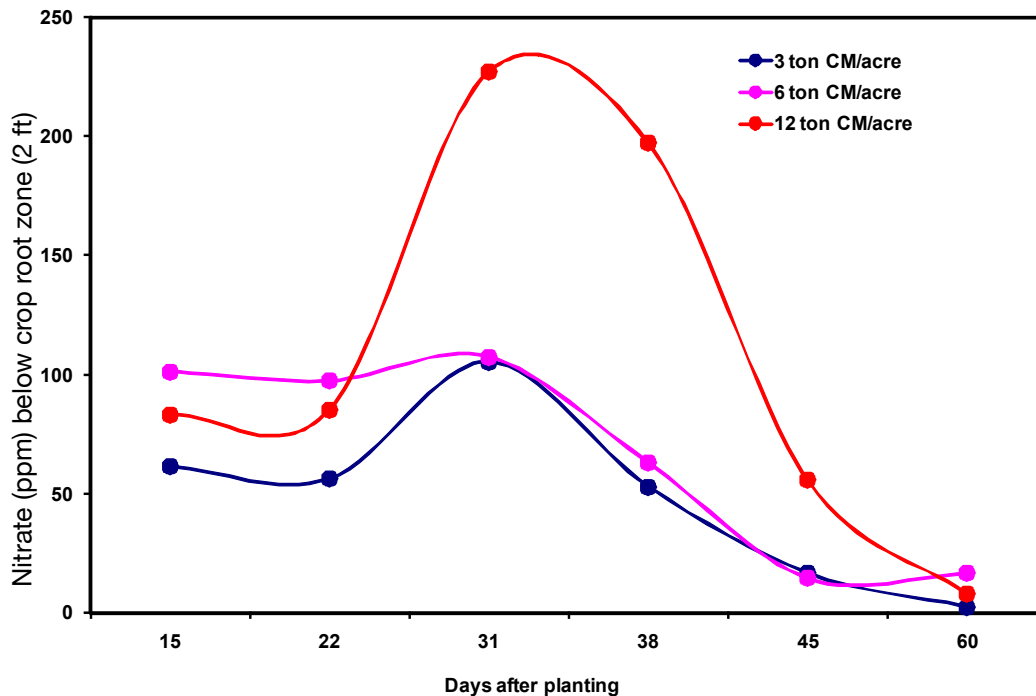


Figure 15: Nitrate leaching can be a problem with organic as well as synthetic amendments. Under ideal soil conditions, organically bound nitrogen is rapidly converted biologically to nitrate (NO₃⁻). Nitrate is highly leachable in soils. Heavy applications of manures can result in large amounts of NO₃⁻ in the soil, runoff from which can lead to environmental and health issues such as algae blooms and “blue baby syndrome.” This figure shows soil water nitrate concentrations leached below the root zone of corn under three rates of chicken manure applied to a Hawaiian soil (after Ahmad et al. 2009). The red curve in the chart indicates excessive levels of nitrates, indicating increased risk of nitrate leaching below crop roots at high applications of manure. The risk of leaching may be mitigated by moderate applications of manures (blue and pink curves in the chart), timing manure applications to meet plant needs, and utilizing grass cover crops to utilize excess NO₃⁻.



Figure 16 (left): Farmer Ned Whitlock of Moloa‘a Organica‘a Farm, Kaua‘i, checks a load of National Organic Program compliant chicken manure shipped from O‘ahu. **Figure 17 (right):** Aged chicken manure bagged for sale, Petersen Farms, O‘ahu.

known as volatilization. Manure should be incorporated after spreading to reduce N loss due to volatilization, and a cover crop, usually a grass, may be planted to prevent losses due to leaching.

COMPOSTS

Composting is a controlled form of biological decomposition in which organic materials are combined and managed to produce a stable or mature product that can promote plant growth several ways. Properly made compost can

- Enhance microbial activity of soils
- Provide plant nutrients
- Ameliorate and buffer acid soils
- Improve efficiency of N fertilizer
- Suppress disease
- Increase water-holding capacity and improve soil structure.

Composting is often used to reduce odor and minimize the risk of human pathogens in manure. It also reduces the risk of nitrogen immobilization (nitrogen robbing) by woody plant residues. One of the most important characteristics of compost is its ratio of carbon to nitrogen by weight (C:N). Finished compost C:N should be about 20:1 to allow for release of plant available nitrogen and avoid “nitrogen robbing” from surrounding soil. In order to produce a compost with the proper C:N, the initial C:N of the combined organic matter used should start at 25–30:1. This usually requires mixing high nitrogen and high carbon materials. “Greens” refer to high nitrogen materials with a C:N < 30:1. “Browns” refer to high carbon materials with a C:N > 30:1. Most people use a rule of thumb for mixing by volume, e.g., 3 parts Browns to 2 parts Greens by volume, although the correct proportions will actually depend on many factors. The most accurate way to establish a pile with a correct C:N ratio is to determine how much carbon and nitrogen is in each material and adjust

Table 2. Browns to Greens ratio

Add the following parts Browns for each part of corresponding Greens by *volume*. For example, use ten buckets of dry leaves for every bucket of vegetable waste. The ratio of carbon to nitrogen (C:N) is listed in parentheses. After Klickitat County, undated.

GREENS	BROWNS				
	Dry leaves (50:1)	Newspaper (55:1)	Office paper (130:1)	Softwood chips (225:1)	Cardboard (380:1)
Chicken manure (6:1)	72	52	21	22	11
Vegetable waste (11:1)	10	7.5	2.8	3.0	1.6
Food waste (15:1)	15	10	3.8	4.4	2.2
Packed grass (15:1)	4.6	3.5	1.3	1.4	0.8
Cattle manure (17:1)	7.0	5.0	1.9	2.1	1.1
Horse manure (27:1)	2	1.5	0.5	0.6	0.3



Figure 18. The effect of amendment C:N ratio on plant growth. From left to right plants received the same amount of nitrogen in amendments with C:N of 35:1, 25:1, 20:1, 10:1, and 5:1.



Figure 19. Effect of compost quality on seedling growth. Eggplant seedlings 4 weeks after seeding in 100% Hawaii-produced compost. Compost C:N ratios were 35:1 and 15:1 from left to right.

for several factors. Table 2 is a quick guide for mixing some readily available organic materials.

Compost is relatively low in available nutrients (e.g., N = 0.5–3%), and large amounts (44–88 metric tons/ha or 20–40 tons/acre) generally need to be applied in the field to observe short term changes in soil quality or plant growth. The transportation and production costs associated with these application rates can be prohibitive. High quality composts may be used in much smaller quantities via water-based extracts (tea) or by including compost in seedling media. Compost quality can vary significantly based upon several factors related to compost maturity.

Compost maturity

Maturity is an important concept that is closely related to the quality of compost. Simply put, mature compost has decomposed enough to promote plant growth. Objective indicators of maturity have been established and are discussed below. Most of these indicators require special equipment or a commercial analysis, and it takes time for results to be received. Experienced producers and users of compost often evaluate maturity using subjective indicators such as color, smell, and feel. Dark brown, earthy-smelling, moist, and finely grained composts that lack sour or ammonia off-odors are expected to be of adequate maturity to promote plant growth. However, more quantitative measures are necessary to enable end-users to determine the optimal rate and frequency of application for a given batch of compost.

C:N ratio

The ratio of carbon to nitrogen in compost is probably the best known objective indicator of compost quality. Optimal C:N range is considered 10–20:1 since composts within this range are unlikely to immobilize plant available nitrogen. Typically, composts with C:N above 25:1 are unacceptable for use in cropping systems. It is important to note that



Figure 20 (left): Turning large compost pile for uniform composting and so that the pile does not overheat. Figure 21 (right): Manual compost turning.

C:N ratios are not adequate as the sole determinant of compost maturity although they are extremely useful in screening compost for acceptable maturity. Compost that has C:N < 25:1 should be further evaluated for other indicators of maturity.

Stability

A common measure of compost maturity is stability, or the potential for compost to further decompose. The most common measure of compost stability are self-heating tests where the maximum rise in temperature of moist compost is measured over a 5–10-day period. Excessive heating (>20°C increase in 10 days) indicates unstable compost. Respiration or carbon dioxide evolution from moistened compost is also used as an indicator of stability. Respiration and self-heating are both indicators of biological activity. While biological activity is considered desirable in composts, unstable compost that has been containerized rapidly consumes oxygen leading to anaerobic conditions and resulting in off-odors and the production of phytotoxic compounds. Unstable composts are also likely to be low in plant-available nutrients.

Plant-available nitrogen

Nitrate and ammonium are important indicators of compost maturity. It is recommended that nitrate concentration be at least 100 ppm for mature compost. Some sources recommend that nitrate and other plant available nitrogen should not exceed 300 ppm when compost is being used as a substrate in growing medium. However, composts with nitrate concentrations of greater than 600–2000 ppm are associated with the best plant growth in greenhouse and field trials in Hawai'i (Pant et al. 2011). Ammonium should be less than 1000 ppm, and the ratio of ammonium to nitrate in the compost should be less than 1:1.



Figure 21. Mechanical compost and manure spreader, Twinbridge Farm, O'ahu.

Compliance with National Organic Program (NOP) standards

For organic certification, use of fertilizers and soil amendments must meet the NOP rule 205.206 management practice standards.

Input	NOP Status	Notes
Aquatic plant products	Allowed	Must not contain prohibited products
Ash	Allowed	Must not contain prohibited products
Animal meals	Allowed	Includes blood, bone, and feather
Cardboard	Restricted	Must not be waxed or impregnated with pesticides. May be used as mulch or compost feed stock
Compost	Allowed	See details above
Biosolids (Humanure)	Prohibited	
Crop Residue	Allowed	Must not contain prohibited products
Plastic mulch	Restricted	Must be removed at end of cycle. Cannot be incorporated.

Other measures of maturity

Other measures of maturity include EC (<2.0 mmo) and pH (6.0–7.5). Compost quality is also indicated by the presence or absence of contaminants. Potential major contaminants include human pathogens and physical contaminants such as plastic, weed seeds, heavy metals, and pesticide residues. Maintaining high temperatures for a period of time during the composting process has been the primary approach towards minimizing contaminants, particularly human pathogens. Screening, which can remove certain physical contaminants, is also recommended.

VERMICOMPOST

Vermicompost is generated from organic materials that have been consumed by worms and associated microorganisms. Common local feedstocks include plant residues, manures, and other organic by-products. In Hawai'i there are several commercial producers of vermicompost using both *Eisenia fetida* (red wigglers or tiger worms) and *Perionyx excavatus* (blue worms), with feedstocks ranging from chicken and pig manure to kitchen scraps and cardboard. Home production of vermicompost is fairly simple, and commonly done. The benefits of vermicompost to seedling vigor and plant health are attributed in large part to high concentrations of plant available macro- and micro nutrients, plant growth promoting organic acids, and high microbial activity, all of which may confer tolerance to stress. Vermicompost quality will vary depending on many factors including worm species, raw material used, and age of the compost. Vermicomposts are generally of finer structure, contain more nutrients, and have higher microbial activity than other types of composts. This makes them particularly valuable as plant growth promoters. Vermicomposts are also widely recognized for their potential to suppress plant disease. One benefit is the relatively large amount of plant available nitrogen that they contain in the form of nitrate (NO₃⁻). This is partly due to the enclosed environment used in vermicomposting



Figure 22. Worms consuming household kitchen scraps mixed with newspaper.

that reduces losses of NO_3^- and other nutrients. Allowing vermicompost to cure (stored in aerated container) for 3–4 months after harvesting can also dramatically increase the NO_3^- content. Cured vermicompost is also well suited for compost tea production, as described below.

COMPOST TEAS

Compost teas are water-based preparations of compost that have a relatively long history in agriculture. They are simple to make by soaking compost in water and agitating by stirring, aeration and other methods. Compost tea allows for beneficial constituents of high quality compost (microorganisms, plant available nutrients and humic substances) to be applied to crops over a larger area and more frequently during the cropping cycle than is possible with soil incorporation. Several growers and landscape managers have been early adopters of compost tea in Hawai'i (Radovich and Arancon 2012). These growers vary in the types of equipment they use to extract the compost, the ratio of water to compost used, and the type of compost they extract. During the past 5–10 years there has been a dramatic increase in the interest and use of compost tea, particularly by new growers. There are several assumptions that many growers make when extracting their compost, including:

1. Biological activity in the compost tea should be high at the time of application,
2. Aeration and additives (e.g., sugars, seaweed extracts, humic acid, etc.) improve the biological quality and efficacy of tea, and
3. Vermicompost is best for producing compost tea.

The above assumptions had not been systematically tested in Hawai'i until recently. Early experiments indicated that spraying the plant canopy alone did not significantly affect yield (unpublished data). Multiple

studies subsequently conducted in the field, greenhouse and laboratory have demonstrated that application of tea to the root zone can significantly increase plant yield and root growth in multiple soil types and media using extraction ratios of 10–100:1 (water:compost) by volume (Pant et al. 2009; Pant et al. 2011; Pant et al. 2012).

Three primary mechanisms have been proposed for increased yields and improved nutrient status of plants receiving compost tea:

1. Extracts directly contribute plant available nutrients,
2. Extracts increase soil biological activity, consequently improving nutrient mineralization and plant availability,
3. Extracts increase nutrient interception via enhanced root growth.

The data have also been used to develop grower recommendations in a handbook for compost tea use in Hawai'i (Radovich and Arancon 2012). Preliminary conclusions and recommendations for compost tea use in Hawai'i include

- Application to the root zone via fertigation is preferable to spraying leaf surfaces in order to maximize efficacy and reduce risk of microbial contamination of leafy greens.
- Short-term compost tea effects are most apparent when plant nutrient availability (especially N) is low to moderate in the growing medium.



Figure 23 (left). Simple compost tea aerated brewer made from readily available parts. Figure 24 (right): Moloka'i Cooperative Extension agent Alton Arakaki demonstrates a small-scale fertigation system used for compost tea and other liquid fertilizers.

- Compost quality is the most important factor affecting tea quality and plant growth promotion.
- Vermicomposts produced in Hawai'i have been determined to be of consistently high quality. Other composts may be used, but should have C:N ratio less than 20:1 and be relatively high in nitrate (e.g., >600 ppm NO₃⁻).
- Aeration is not necessary for the extraction of compost tea, but can speed up the process.
- Evidence from Hawai'i research suggests that biological activity during the composting and extraction process is more important than biological activity in the tea at the time of application.
- Extraction ratios of 10:1–100:1 (water:compost) by volume are recommended.

BIOCHAR

Organic residues that are high in carbon may be pyrolyzed (heated at high temperature under low/no oxygen conditions) to produce a stabilized charcoal, commonly called biochar. The stability of properly made



Figure 25 (top left): Small-scale biochar production demonstration on Maui constructed from readily available materials. Figure 26 (right): Turning biochar into the soil manually. Figure 27 (bottom left): Biochar milled to a fine-grained product for incorporating into the soil.

biochar makes it attractive as a method of carbon sequestration. The chemical and physical structure of biochar make it a potentially beneficial amendment in tropical soils to raise pH, increase nutrient retention, and improve plant growth. There is ample anecdotal evidence and a growing body of scientific literature to suggest that biochar is a valuable, yet underutilized input for local agriculture. However, there is still much to learn about the material. The mechanisms for the beneficial effects of biochar are not fully understood. They are thought to include high porosity and surface area that retain nutrients and enhance soil biology. Also included are chemically reactive groups, such as COOH, OH, and ketone, that give biochar a high potential to adsorb toxic substances, such as aluminum (Al) and manganese (Mn) in acid soils and arsenic (As) and cadmium (Cd) in heavy metal contaminated soils (Berek et al. 2011; Hunt, et al. 2010). Consequently, biochar may have the most potential benefit in soils that are highly weathered, acidic, and/or low in organic matter.

Feedstock type and production method are thought to be the biggest factors affecting biochar quality, and these can vary widely (Hunt, et al. 2010). Perhaps the most important quality characteristic is the level of volatile matter (VM) such as tars and resins, which are low in properly produced biochar. High levels of VM may suppress plant growth via immobilization of nutrients in the soil (Deenik et al. 2010). Char with high levels of VM can be identified by a high degree of hydrophobicity or water repellency. With training, one can make high quality biochar on the farm with simple equipment (see Figure 25). Recommendations for application include soil incorporation of biochar screened to 1 cm (0.5 in) or smaller pieces into the root zone. Reported application rates tend to be high (56–112 metric tons/ha or 25–50 tons/acre), but applications as low as 18 metric tons/ha (8 tons/acre) may have some benefit (Josiah Hunt, personal communication).

AQUATIC PLANTS

Seaweed/Algae

Invasive algae, a major threat to coral reefs throughout Hawai'i, is unsurpassed as a potential local source of potassium, an essential plant nutrient required in relatively large quantities. Invasive algae are currently available in large quantities in some parts of the state where reef remediation efforts are ongoing. Innovative growers have been collecting the material from conservation groups and applying it to fields directly raw or after composting. Nutrient content depends heavily on species and may also vary with location. Invasive species high in K (e.g., *Gracilaria salicornia*, *Kappaphycus* spp., and *K. striatum*) infest many locations across the state and have been routinely applied in high rainfall areas without salinity problems. In Maunaloa bay on O'ahu, the dominant species, *Aravinvillea amadelphia*, was very low in K compared to other species also collected in the area (see Appendix 1). Rates of application vary significantly across farms. For a farm in a high rainfall area, estimated application rates of a high K species to taro (*Colocasia esculenta*) and



Figure 28 (left): Volunteers harvesting invasive limu at Maunalua bay, Kaneohe, O’ahu. **Figure 29 (right):** Mixed invasive seaweed species collected from Kaneohe Bay, O’ahu.

sweetpotato (*Ipomoea batatas*) are 5700 kg/ha (5100 lb/acre) on a dry weight basis. An algae concentration of 10% K dry weight, for example, is equivalent to 570 kg/ha (510 lb/acre) of K.

Public and private partnerships have been formed to achieve multiple objectives identified as essential to optimizing invasive algae as an agricultural input (Franklin 2010). These objectives include: elucidating location and species effects on mineral nutrient concentrations; estimating acceptable loading rates of salts and metals from the algal applications for selected Hawaiian soils; and optimizing processing procedures for salt reduction and maximum nutrient content.

Azolla (*Azolla* spp.)

Azolla is a small, fast-growing freshwater aquatic fern that can be grown on-farm and harvested for mulch, compost, and animal feed. Its rapid growth is facilitated by a symbiotic relationship with a type of nitrogen fixing organism, a cyanobacteria called *Anabaena azollae*, which allows azolla to fix up to 1000 kg/ha (890 lb/acre) of N per year. Under optimal conditions, azolla can double in weight every 24 hours (Ferentinos et al. 2002). It is frequently used in flooded cultivation of rice or taro to cover the water surface and suppress weed growth. After harvest, the fields are drained and the azolla becomes mulch or is incorporated into the soil. Azolla can also be harvested for use in mulching crops, making compost, and feeding pigs and poultry.

Water lettuce (*Pistia stratiotes*)

Water hyacinth (*Eichornia crassipes*)

Water hyacinth and water lettuce are both rapidly growing freshwater plants that can produce large amounts of biomass. Water hyacinth has been found to be capable of doubling its biomass every seven days and yielding 60–110 tons of dry matter/ha/year and water lettuce is capable of yielding 50–80 tons of dry matter/ha/year (Gumbricht 1993). Because of their rapid growth, these species can cover ponds and lakes, blocking out light and gas exchange with the air. Their abundant growth can also

crowd out other plant species and make the environment uninhabitable for fish and other aquatic animals. Because of this potential, these plants are often considered invasive pests. However, in on-farm ponds where their expansion can easily be controlled through harvesting, water hyacinth and water lettuce are a viable source of long-lasting mulch and compost material.



Figure 30. Azolla is a rapidly growing, nitrogen-fixing aquatic fern that is capable of producing large quantities of biomass for mulch, compost, and animal feed.



Figure 31. Water lettuce is a productive aquatic plant that can be used for mulch and compost feedstock, pictured here growing in a pond at John Pollock's Farm in Ulupalakua, Maui.

TANKAGE

Tankage is the solid by-product of animal waste rendering. Tankage is unsurpassed as a local, organic source of nitrogen, containing more than five times the nitrogen of most composts or aged manures. It is particularly useful for high nitrogen demanding crops like corn, and for speeding up the decomposition of woody green residues. Although the nutrient content of tankage varies with feedstock, the product available in Hawai'i has consistently been analyzed at 8–9% N, 2.5–3.5% K, 0.75–1% P and 5.0% Ca with a C:N of 5:1 (Arakaki 2008; Garcia and Rosentrater 2008; unpublished data). Similar numbers have been observed in material from American Samoa. The relatively low P content is due to the Hawai'i material being derived primarily from fish scraps and waste meat from food distributors (the Samoan material is exclusively fish scraps from canning operations), and contains little bone. Sometimes called meat and bone meal, tankage has been documented as a valuable agricultural input and has been utilized in Hawai'i for at least 20 years (Valenzuela et al. 2000).

The primary agricultural use of tankage is as a supplemental N source, especially for, but not limited to, certified organic growers. The material has been recognized as National Organic Program (NOP) compliant by certifying agencies in the state. Demand for the product continues to grow proportionally to the rising cost of synthetic fertilizer. The need for recommended application rates to guide growers is increasingly apparent. Research has identified application rates of 2.2–4.4 metric tons/ha (1–2 tons/acre) as adequate for plant growth, with excessive rates of 9 metric tons/ha (4 tons/acre) suppressing yields (Valenzuela et al. 2000; Arakaki et al. 2008; Figure 2). Preliminary recommendations for most short-cycle vegetable crops are 1700–3400 kg/ha (1,500–3,000 lb/



Figure 32. Island Commodities Manager (ret.) Carl Tanaka displays the tankage produced on O‘ahu. New rendering plants are planned for Hawai‘i Island and elsewhere in the state.

acre) per crop cycle. Residual nitrogen availability has been observed in subsequent crop cycles at rates exceeding 2.2 metric tons/ha (1 ton/acre), and frequent use of the material should be accompanied by regular soil testing to avoid excess nitrogen. On-going research is focused on

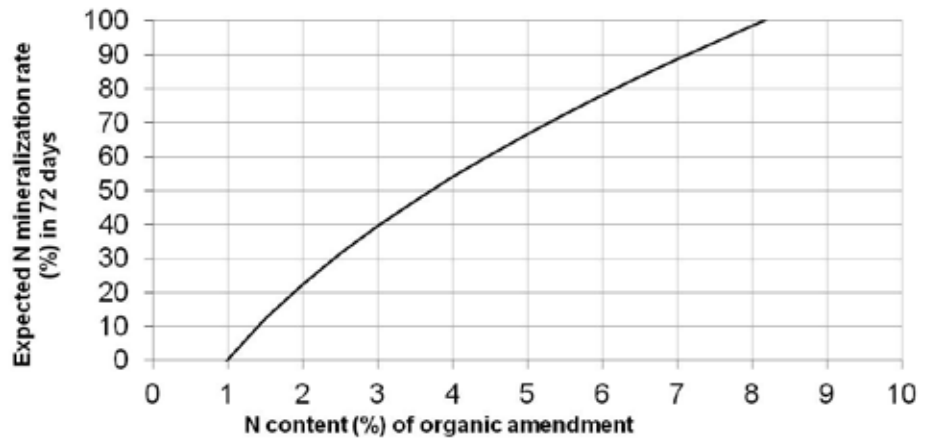


Figure 33. Idealized nitrogen release rate based on amendment nitrogen content. After Vigil and Kissel (1991). This chart suggests the potential nitrogen availability to plants based on the nitrogen content of organic fertilizers and green manures. For example, when using tankage (8–9% N), over 90% of the N is expected be mineralized within 72 days, compared to just over 50% of pelletized chicken manure (4% nitrogen). It is important to note that not all mineralized nitrogen will necessarily be available to plants, e.g., losses may occur due to leaching, volatilization, and immobilization by microorganisms.

determining the range of recommended rates for specific crops and soil types in Hawai'i. Currently there is a single tankage production plant in Hawai'i outputting approximately 67 metric tons (60 tons) per month. Increased production will be necessary if tankage is to serve as a significant, sustained source of agricultural nitrogen in Hawai'i.

KOREAN NATURAL FARMING

Korean Natural Farming (KNF) is an approach to agricultural production that is gaining popularity, in part because of its focus on using local inputs and reducing the need for total inputs over time. The KNF approach to natural farming has been recently popularized in the Pacific by Professor Han Kyu Cho. Similar methods employing microorganisms and fermentation preparations have been utilized throughout Asia for centuries, and are alternatively called Asian Natural Farming or just Natural Farming. The primary inputs used in KNF are 1) Indigenous microorganisms (IMO), and 2) foliar sprays made from various herb and mineral preparations. The use of no-till practices and mulching are also central tenets of KNF and other natural farming systems.

Model piggeries in Hawai'i have clearly demonstrated the potential for IMO preparations to reduce odor and fly problems in animal operations (DuPont and Fischer, 2012). Evidence on the value of KNF in vegetable



Figure 34. Various ingredients used in making indigenous microorganism soil amendments and various preparations in Korean Natural Farming.

production systems has been increasing in recent years. Replicated trials on multiple farms in Hawai'i have shown that KNF can enhance free-living nematodes that play key roles in soil nutrient cycling and increase the abundance of other soil fauna such as enchytraeid worms that improve soil tilth (Wang et al., 2013).

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Appendix 1. Total nutrient content of select synthetic and organic amendments. Modified from Hue and Silva 2000.

Material	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu
	% dry weight						ppm (mg/kg) of dry weight			
Imported chemical fertilizers										
Urea	46	-	-	-	-	-	-	-	-	-
Potassium nitrate	13	-	44	-	-	-	-	-	-	-
Treble superphosphate	-	45	-	-	-	-	-	-	-	-
Animal Manure/mortalities										
Poultry (broiler) manure ^a	4.4	2.1	2.6	2.3	1.0	0.6	1000	413	480	172
Dairy cow manure	2.4	0.7	2.1	1.4	0.8	0.3	1800	165	165	30
Swine manure ^c	2.1	0.8	1.2	1.6	0.3	0.3	1100	182	390	150
Sheep manure ^c	3.5	0.6	1.0	0.5	0.2	0.2	-	150	175	30
Horse manure ^c	1.4	0.4	1.0	1.6	0.6	0.3	-	200	125	25
Feedlot cattle manure ^d	1.9	0.7	2.0	1.3	0.7	0.5	5000	40	8	2
Composted chicken (layer) manure ^b	2.3	3.5	2.9	15.5	1.3	-	-	-	-	-
Tankage (meat and bone meal) ^g	10.16	3.12	0.85	5.52	0.17	-	695	6.52	91.8	11.6
Plant residues										
Young rye green manure	2.5	0.2	2.1	0.1	0.05	0.04	100	50	40	5
Cowpea green manure ^e	3.6	0.4	3.5	1.5	0.4	-	-	-	-	-
<i>Leucaena</i> green manure ^e	3.8	0.2	1.7	1.1	0.3	-	-	-	-	-
Composted plant residue ^k	1.1	0.3	0.7	4.8	1.0	-	26835	532	204	90
Seaweed species^j										
<i>Aravinvillea amadephia</i>	0.58	0.05	0.28	28.3	2.1	-	11505	206	1.9	8
<i>Acanthophora spicifera</i>	1.51	0.05	3.1	3.23	1.29	-	1432	50	7.4	6.0
<i>Gracilaria salicornia</i>	1.38	0.10	11.2	5.19	0.98	-	3406	522	21.7	10.3
<i>Kappaphycus alvarezii</i>	0.56	0.04	21.5	0.18	0.35	-	52.1	3	20.6	2.27
<i>Eucheuma</i> spp.	0.86	0.07	17.5	0.73	0.62	-	84.7	14	17.5	2.01
Biosolids										
Anaerobically digested ^h	5.2	0.6	0.06	1.5	0.3	-	15000	80	1000	400
Primary ⁱ	1.8	0.4	0.03	0.8	0.1	-	8000	200	450	300

^aComposition estimated from means of approximately 800 and 400 samples analyzed by the University of Maryland manure analysis program from 1985 to 1990.

^bSilva, J.A., et al. 1995. The use of composted poultry manure as a fertilizer. In: Hawaii Agriculture: Positioning for Growth. College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa.

^cCalculated from North Carolina Cooperative Extension Service Soil Fact Sheets prepared by Zublena et al. (1993).

^dComposition based on average analysis reported in Eghball and Power (1994), Beef cattle feedlot manure management. J. Soil and Water Conserv., 49: 113-122.

^eHue, N.V., and I. Amien. 1989. Aluminum detoxification with green manures. Comm. Soil Sci Plant Anal. 20: 1499-1511.

^fEach value is a mean of nine samples. Analysis were conducted at ADSC of the University of Hawaii at Manoa.

^gEach value is a mean of six samples. Tankage samples were collected 2011-2012 from Island Commodities, Kapolei, Hawaii.

^hHue, N.V., and S.A. Ranjith. 1994. Sewage sludge in Hawaii. Chemical composition and reactions with soils and plants. Water, Air, and Soil Poll. 72: 265-283.

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^kRadovich, unpublished data. Each value is a mean of 28 analyses of composts derived primarily from wood chips and municipal greenwastes with no manure or mortalities. See also Radovich and Arancon (eds.). 2012. Tea Time in The Tropics. http://mysare.sare.org/mySARE/assocfiles/937966Compost_tea_manual.pdf

Appendix 2. Select cover crop characteristics and notes on management for Hawai'i.

Common name	Botanical name	Seed Rate ^m	Weed Risk Assessment ⁿ	Notes
Grasses				
Oats	<i>Avena sativa</i>	70–140	N/A	Excellent weed suppression, good biomass production. Can host rust and root knot nematode.
Sorghum × Sudan grass	<i>Sorghum bicolor</i> × <i>S. bicolor</i> var. <i>sudanense</i>	40–50	N/A	Excellent nutrient scavenging, heavy biomass production. Poor host for root knot nematode. Large root mass tolerates mowing, resists incorporation.
Sudan grass	<i>Sorghum bicolor</i> subsp. <i>drummondii</i>	30–40	N/A	Good biomass production, good weed suppression. Easier to incorporate and kill than Sorghum × Sudan grass. More tolerant of hot weather than oats.
Cereal rye	<i>Secale cereale</i>	70–160	N/A	Reportedly good biomass production and weed suppression, although growth at sea level has been mediocre. Less utilized than oats. May suppress growth and germination of other plants via allelopathy. Good host for root knot nematode.
Annual ryegrass	<i>Lolium multiflorum</i>	5–30	High (9)	Excellent erosion control. Good host for root knot nematode.
Japanese millet	<i>Echinochloa</i> spp.	10–30	High (8)	Excellent weed suppression, good biomass production. May host root knot nematodes.
Legumes				
Sunn hemp	<i>Crotalaria juncea</i>	30–60	Low (-3)	Good N-fixation capacity, excellent suppression of nematodes and weeds. Lower biomass production under short-days, which initiates flowering. Incorporation is challenging as plants age and become fibrous.
Lablab	<i>Lablab purpureus</i>	5–20	Low (-1)	A good host for root knot nematode. Aggressive, climbing nature makes it challenging to manage in vegetable systems. Excellent long term weed suppression.
Velvet bean	<i>Mucuna</i> spp.	45–90	High (7)	Slow to establish, good biomass over long-term.
Alfalfa	<i>Medicago sativa</i>	20–50 ^l	N/A	Varieties differ in their adaptability to local conditions. Good host of root knot nematode.
Sweet clover	<i>Melilotus alba</i>	30–70	N/A	Very deep taproot, drought tolerant after establishment. Tolerates mowing well.
Hairy vetch	<i>Vicia villosa</i> spp. <i>dasycarpa</i>	30–60	N/A	Aggressive, climbing, good early weed suppression. Host to root knot nematode and <i>Sclerotinia minor</i> , which causes lettuce drop.
Glycine	<i>Neonotonia wightii</i>	40–50	High (7)	A poor host for root knot nematode. Aggressive, climbing nature makes it challenging to manage in living mulch systems. May host <i>Sclerotinia</i> and <i>Scercospera</i> . Generally not recommended due to high potential for weediness.
Cowpea	<i>Vigna unguiculata</i>	70–120	N/A	High susceptibility to a range of pests and diseases has limited the use of cowpea despite its potential for biomass production and N-fixation.
Other				
Buckwheat	<i>Fagopyrum esculentum</i>	50–100	N/A	Extremely fast canopy closure, good weed suppression, attracts beneficial insects. Canopy senesces quickly. Used for early (nurse) cover. Good host of root knot nematode.
Mustard, rape, radish	<i>Brassica</i> spp.	5–20	High (16)	Rapid ground cover, good early weed suppression. Some potential for biofumigation that may temporarily reduce soil biological activity. Can host nematodes, a wide range of caterpillars, white rust and other pests of the <i>Brassicaceae</i> .
Marigold	<i>Tagetes</i> spp.	2–10	N/A	Suppresses nematodes. Suppressant effect is dependent on marigold and nematode species. Hosts mites and thrips.

^m Seed rates listed are for broadcast application. Rates for drilling seed may be considerably lower (Valenzuela and Smith 2002; <http://www.ctahr.hawaii.edu/sustainag/cc-gm/index.html>)

ⁿ Hawaii Weed Risk Assessment (WRA) <http://www.botany.hawaii.edu/faculty/daehler/wra/>

APPENDIX 3: DEFINITIONS

- Biological nitrogen fixation—A process in which bacteria convert gaseous nitrogen in the air to ammonium, often in a symbiotic relationship with legumes.
- Char—A stabilized charcoal produced from high carbon organic residues via pyrolyzation (burning at high temperature under low/no oxygen conditions).
- Compost tea—Aqueous extracts of compost. May include simple water leachates or prolonged active extraction with or without additives to enhance microbial activity.
- Compost—The product of controlled biological decomposition of organic feedstocks before addition to the soil.
- Cover crop—a crop grown primarily to improve farm system function by protecting topsoil, suppressing weeds and other pests, providing habitat for beneficial insects, increasing soil organic matter and/or improving nutrient availability.
- Fertilizer—Inputs applied to soil or plants primarily to supply nutrients in the short term.
- Green manure—Fresh plant residues, usually from a cover crop or alley crop in the same or nearby location, that are applied to the soil to improve fertility.
- Greenwaste—Uncomposted plant residues.
- Inoculation—Adding beneficial microorganisms to seeds, soil or plants. Often done with rhizobia bacteria for nitrogen fixation in legumes or mycorrhizal fungi for many species.
- Living mulch—A crop or cover crop that serves as a mulch to another crop grown in the same space and time. Examples include perennial peanut in fruit orchards and pumpkin/squash in the traditional Native American “Three Sisters” corn-bean-squash polycrop system.
- Mineralization—Microbial conversion of organic nutrients into plant available forms. For example, the mineralization of organic nitrogen by microorganisms to plant available ammonium (also called ammonification).
- Mulch—Nonliving soil cover (including plastic) used to suppress weeds, conserve moisture, protect soil. Organic mulches may also contribute organic matter to the soil.
- Organic matter—The biological component of the soil that includes living organisms, fresh and decomposing (labile) residues, and fully decomposed (non-labile) humic substances.
- Soil amendment—any input applied to the soil to improve its ability to support plant growth through physical, chemical and/or biological means.
- Soil fertility—Ability of the soil to supply plants with essential nutrients in the short and long term.
- Tankage—The solid, ground by-product of animal rendering. A good source of organic nitrogen.