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Copper Supplementation for Beef Cattle in Hawai‘i

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Healthy beef cattle diets are composed of suitable amounts of four primary nutrients: energy (carbohydrates and fats), protein, minerals and vitamins, and water necessary to meet the specific needs of the animal in its current physiological state (e.g., growing, lactating, dry, etc.). Foraging beef cattle acquire their energy, protein, minerals, and vitamins primarily from the plants they graze. There are many factors that determine the relative ratio of these essential nutrients (a measure of forage quality) available to the grazing animal, including the type, quantity, and relative abundance of forages (grass, legume, etc.) in the pasture; the level of maturity of the forages; the soils they grow on; and the climate. For example, the quantity and relative abundance of good-quality forages compared to poor-quality or unpalatable forages can vary across and/or between pastures. Likewise, soils with greater fertility have the potential to produce a greater quantity and quality of forages compared to soils of lower fertility. Finally, during drought conditions, forage production will decrease and be of poorer quality than when precipitation is normal. All of these factors converge to determine the quality of the forage available to the grazing animal. When the forages being consumed do not meet the dietary needs of the grazing animal, deficiencies may develop that will negatively impact the animal's health, growth, and productivity. This in turn can affect ranch profitability. Thus, savvy producers provide supplementation when forages do not meet one or more of the dietary needs of their herd to prevent a decline in health and productivity and a potential loss in ranch profit.

In grass-based beef-production systems, certain circumstances such as drought can create negative energy and protein balances that require supplementation. Thus, choosing when to supplement energy and protein is typically based on particular events and circumstances. Conversely, mineral and vitamin deficiencies are more common and occur with greater consistency, so often continuous mineral supplementation is required. A good mineral supplementation program is essential for good herd health and productivity. To understand what comprises a good mineral supplementation program, producers need to have a sound knowledge of the dynamics of the mineral components necessary for animal health and production.

Livestock mineral requirements are divided into macro-minerals, those required in relatively large amounts, and micro-minerals, those required in smaller amounts (Table 1). Each mineral, whether required in large amounts or small, plays an important role in the animal's health, from supporting strong bones, growth, and reproduction to maintaining metabolic and enzymatic functions (Table 1). Thus, a deficiency in any one of these key minerals can have an impact on the health of your herd.

Copper (Cu) is one of the key minerals that is most commonly deficient in beef cattle consuming grass-based diets (McDowell 2003, Suttle 2010), including in Hawai‘i. A deficiency in copper can develop due to insufficient copper in the forage or feed (commonly referred to as a primary deficiency) and/or because of antagonistic reactions with other minerals like iron (Fe), molybdenum

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Table 1. List of macro- and micro-minerals required for healthy beef cattle diets, their major known functions, and most common sources.

Mineral	Most Significant Known Functions	Sources
Macro-Minerals (required in larger amounts)		
Calcium	Bone and teeth formation, nerve and muscle function	Forages, legumes, mineral supplement
Phosphorus	Reproduction, health of bones and teeth	Grains, forages, mineral supplement
Magnesium	Growth, reproduction, metabolic functions	Forages, mineral supplement
Potassium	Metabolic functions	Forages, mineral supplement
Sulfur	Metabolic functions, amino acid formation in rumen	Forages, grains, and mineral supplement
Sodium/Chloride	Regulate pH; nervous and muscular system function	Mineral supplement
Micro-Minerals (required in smaller amounts)		
Chromium	Immune response, glucose tolerance factor	Forages, cereal grains, TMS*
Cobalt	Component of Vitamin B_{12}	Legumes, forages, TMS
Copper	Hemoglobin formation, tissue metabolism	Forages, grains, mineral supplement
Iodine	Production of thyroid hormones, energy metabolism	Forages, TMS
Manganese	Reproduction, enzyme formation	Forages, mineral supplement
Molybdenum	Enzyme activity	Forages, mineral supplement
Selenium	Antioxidant, glutathione peroxidase	Grains, forages, mineral supplement
Zinc	Enzyme activity	Legumes, forages, mineral supplement

***Trace mineral salt**

(Mo), and sulfur (S) (secondary deficiency). Copper deficiency is easily diagnosed and corrected with a well-designed mineral supplementation program. The following discussion will focus on the importance of copper in cattle diets, the diagnosis and effects of deficiencies in copper, the copper content of Hawai‘i forages, and how to evaluate copper levels in pasture forages.

Importance of Copper in Cattle Diets

Copper Requirements and Role in Normal Body Function

All classes of cattle (growing/finishing, gestating/lactating, and dry) require a minimum of 10 ppm of copper on a dry-matter basis (NRC 2016). The Maximum Tolerable Concentration (MTC) for copper is thought to be around 40 ppm (NRC, 2016). However, the actual concentration of copper needed in the diet depends on the concentration of antagonist minerals such as iron, molybdenum, and sulfur, which decrease copper absorption in the rumen of the animal (Table 2). Dietary copper requirements increase when dietary iron, molybdenum, and sulfur exceed 200 ppm, 1 ppm, and 0.20% of dry matter (DM) respectively, to compensate for reduced copper absorption in the rumen (Table 2).

Copper is necessary for enzyme, cardiovascular, and immune function as well as reproduction, iron utilization, and bone formation (McDowell, 2003). Cows not receiving adequate copper can exhibit decreases in reproductive performance, including decreased conception rates and increased occurrence of aborted calves. A survey of 318 cows reported that 87.9% of cows that aborted their calves were copper-deficient, whereas only 11.7% of cows which calved were copper deficient (Figure 1), indicating a relationship between copper-deficiency and ability of a cow to carry a calf to term (Sakhaee and Kazeminia 2011). Garcia et al. (2011) observed a decreased conception rate of 36% in copper-deficient heifers compared to 85% in copper-sufficient heifers (Figure 2). Further, copper-deficient calves and calves from copper-deficient cows have decreased growth performance, increased incidence of diarrhea, and increased occurrence of heart failure (Enjalbert et al. 2006). Copper-deficient calves have weakened immune responses when exposed to multiple pathogens, including pathogens involved in the bovine respiratory disease complex, and calves from copper-deficient cows can have poor response to vaccina-

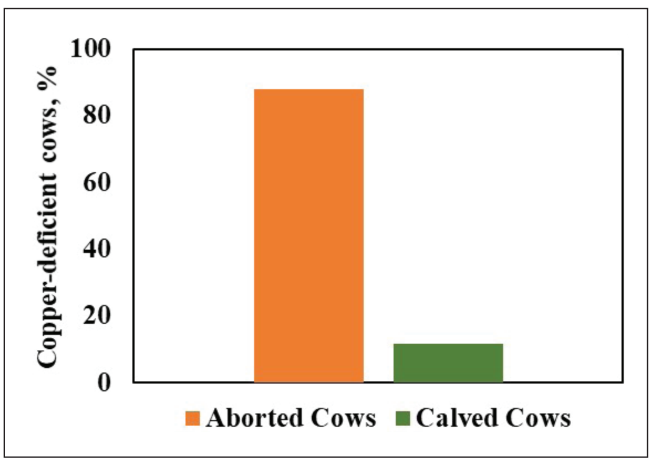


Figure 1. Impact of copper (Cu) deficiency on abortion rates in beef cows. Blood samples were collected and plasma was analyzed for copper concentration from 318 cows, of which 198 were aborting and 120 recently calved. Of the aborting cows, 87.9% were Cu-deficient; however, only 11.7% of the recently calved cows were Cu-deficient (Sakhaee and Kazeminia 2011).

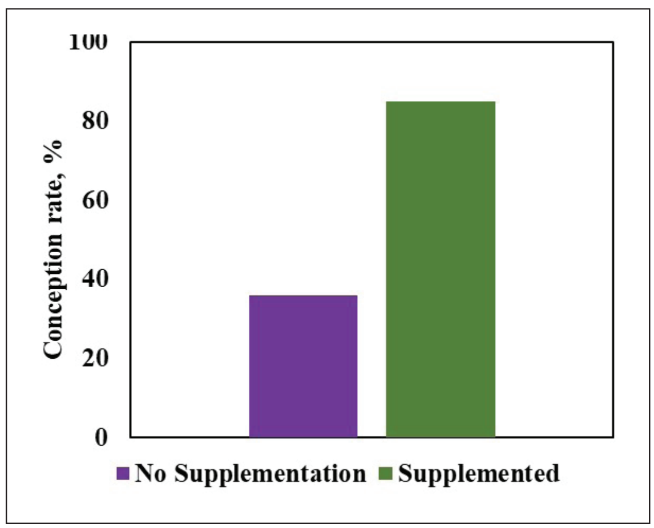


Figure 2. Impact of copper (Cu) supplementation on conception rates in beef heifers. One hundred-twenty heifers were placed in a grazing-based system. Heifers were separated into two groups: one group receiving a Cu sulfate injection and the second only receiving no Cu supplementation (control). Heifers were then observed for reproductive performance. Control heifers had a 36% conception rate, whereas the heifers that received Cu sulfate injections had an 85% conception rate (Garcia et al. 2006).

Table 2. Copper (Cu) absorption in the rumen is decreased by antagonistic minerals iron (Fe), molybdenum (Mo), and sulfur (S) when they exceed certain concentrations in the diet.

Copper Antagonist	Deficient	Ideal	Antagonistic Level**		MTC*
			Marginal	High	
Iron (ppm)	< 50	50–200	> 200–400	> 400	1000
Molybdenum (ppm)	Not established	< 1	1–3	> 3	5
Sulfur (% DM)	< 0.10	0.15–0.20	> 0.20–0.30	> 0.30	0.4

***Maximum Tolerable Concentration**
**** Levels above these can potentially adversely affect copper availability.**

tions and anthelmintics, making them more vulnerable to disease and parasite infection. A study by Stabel et al. (1993) reported copper-sufficient calves had greater serum titer values compared to copper-deficient calves when exposed to both infectious bovine rhinotracheitis virus (IBRV) and *Mannheimia haemolytica* (Figure 3) pathogens which are in the Bovine Respiratory Disease (BRD) Complex. Serum titers are representative of antibodies present in the blood and are indicative of an animal's ability to mount an effective immune response. Copper-supplemented cattle had a 5–18% increase in feed efficiency and up to a 17% increase in average daily gain, compared to growing cattle not supplemented with copper (Gengelbach et al. 1994, Ward and Spears 1997). In addition to improvements in growth performance, copper-sufficient cattle tend to have improved carcass traits compared to copper-deficient cattle (Ward and Spears 1997).

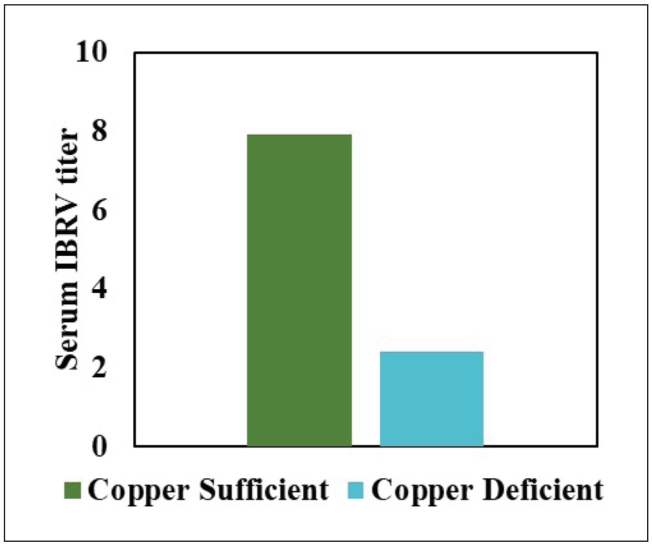
Absorption and Antagonists

Copper, like most other nutrients, is primarily absorbed in the small intestine. Absorbed copper is either transported through the blood to sites of metabolic need and then utilized or stored in the liver when absorbed levels exceed the metabolic demand. Liver storage of copper is regulated through biliary secretion and urinary/fecal excretion (Suttle 2010). Copper absorption is influenced by its source, i.e., organic vs. inorganic copper sources, as well as interactions that may occur in the rumen. As noted earlier, there are three main mineral antagonists that negatively impact copper absorption in cattle: molybdenum, sulfur, and iron (McDowell, 2003; Suttle, 2010). Complex processes in the rumen produce sulfur–molybdenum and sulfur–iron compounds, both of which bind to copper. Sulfur and iron also bind directly to copper (Figure 4). These compounds are relatively unabsorbed by the animal and are excreted in the manure (Suttle 1991, Gould and Kendall 2010). Thus, it is important to know the concentrations of these minerals in forages in order to determine how much copper is available for absorption in grazing cattle.

Copper Deficiency in Cattle

Clinical Signs of Copper Deficiency

Copper is an important component of many proteins and enzymes required for proper physiological functions; therefore, primary or secondary deficiencies of copper can cause clinical signs and lesions across many body systems (integumentary, musculoskeletal, cardiovascular, neurologic, reproductive, immune, etc.). The most common indicator of copper deficiency is changes in hair color and texture. Copper is required to produce the pigment melanin, and therefore copper-deficient black-hided cattle will develop a reddish (rust) tint to the hair along their back, ribs, brisket, and points on the head (topknot and ears), whereas red-hided cattle will develop a yellowish tint to the hair in the same areas. These changes are commonly mistaken for sun-bleaching or fading (Figure 5). In all cases, the hair may become rough, uneven in length, and brittle.



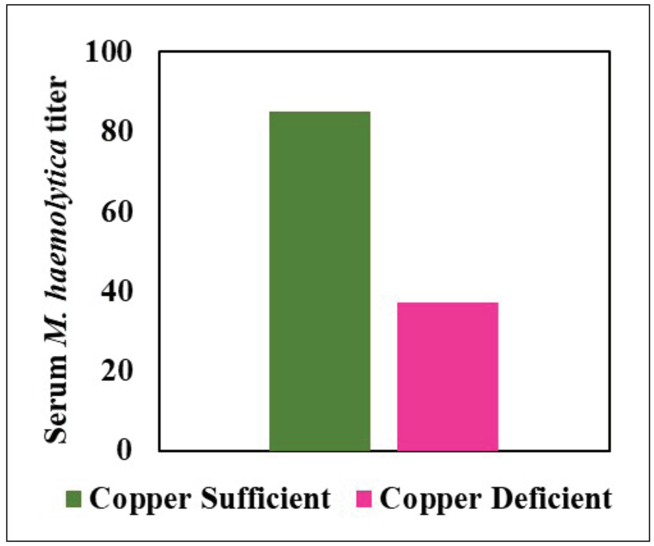


Figure 3. Impact of copper (Cu)-deficiency on immune function. Fourteen calves were fed either a Cu-sufficient or a Cu-deficient diet and exposed to both infectious bovine rhinotrachetitis virus (IBRV) and Mannheimia haemolytica. Serum samples were collected and analyzed for IBRV and M. haemolytica antibody titer concentrations: a) Serum IBRV antibody titer concentrations for Cu-deficient and sufficient calves; b) Serum M. haemolytica antibody titer concentrations for Cu-deficient and sufficient calves (Stabel et al. 1993).

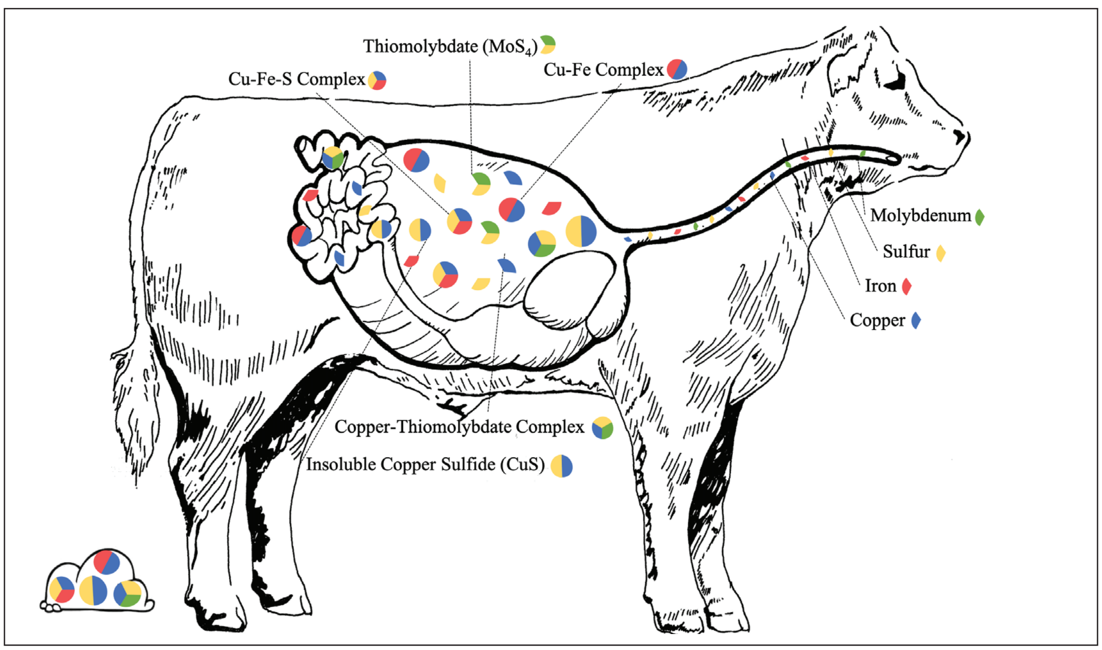


Figure 4. Chemical interactions of copper with molybdenum, iron, and sulfur in cattle digestive systems. Dietary copper (Cu), molybdenum (Mo), sulfur (S), and iron (Fe) enter the gastrointestinal tract and are transported through the reticulum to the rumen. Within the rumen, mineral complexes dissociate and form free-floating minerals. When there are large concentrations of S, S will bind to Mo forming thiomolybdates. Thiomolybdates are Cu-hungry and tightly bind to Cu. Additionally, S binds to Cu, Fe and S bind to Cu, and Fe binds to Cu. These Cu-bound complexes are unable to be absorbed in the small intestine and utilized by the animal. This process results in a significant amount of dietary Cu being excreted in the feces.

The copper-containing enzyme lysyl oxidase is responsible for proper cross-linkage of collagen and elastin. Thus, copper-deficient animals can exhibit musculoskeletal problems such as a "knock-kneed" appearance, swelling of the joints, splaying of the hooves, and pathologic fractures. Affected calves may have straight pasterns and appear to have contracted tendons. If the connective tissues of the cardiovascular system are involved, sudden death (aka "Falling Disease") can be seen, which is a syndrome in which apparently healthy adult animals will suddenly fall on their sides, struggle, and die. Other clinical signs attributed to primary or secondary copper deficiency include diarrhea, hindlimb weakness or paralysis (calves), infertility, anemia, decreased nonspecific immune function, and decreased resistance to illness (Maas 2007, Suttle 2010).

Detecting Copper Deficiencies in Your Herd

To detect deficiencies in copper (or other minerals) in the herd, it is important to have an effective herd-monitoring plan in place. This plan should include frequent visual inspection of the animals in the herd, noting general health, appearance, and activity levels of the animals. Changes in behavior or displays of non-typical behaviors like panting, sluggishness, or not grazing may be early signs of developing health issues. Changes in hair coat color and texture or a general unthrifty appearance are often the first physical signs of copper deficiency. In addition to frequent observations of general appearance and activity, a good herd-monitoring program will track four key indicators: calf **G**rowth, **O**pen cows, **L**ength of calving season, and calf **D**eath loss (the bolded letters forming the acronym **GOLD).** If any of these indicators are below industry standards, then nutrition is likely not adequate and nutrient supplementation may be necessary to correct the problem.

At the first sign of a copper-deficiency issue, action should be taken to diagnose and correct it. Left unchecked, the issue could develop into a chronic condition with more severe symptoms like those discussed previously. If you observe any of these symptoms, it is best to contact your local large-animal veterinarian or Extension agent. Copper deficiencies can be detected using both blood plasma and liver samples; however, liver samples are the preferred and most accurate form of detection, since liver copper levels are more indicative of whole-body reserves compared to blood plasma levels. Blood levels of copper will remain within the normal range even after liver levels start to decrease and therefore can only be used to detect advanced deficiency. Normal blood copper is between 0.6 and 1.5 µg/mL copper, and levels less than 0.6 µg/mL copper are interpreted as deficient. Normal liver copper ranges from 100 to 400 ppm copper (McDowell 2003). Liver samples collected post-mortem can also be used to monitor copper levels. Kidney tissue samples may also be used to measure copper levels but cannot be collected easily from live animals.

Figure 5. Examples of hair discoloration and rough hair coat in black-hided cattle in Hawai'i caused by copper (Cu) deficiency. Photos courtesy of Melelani Oshiro.

Copper in Hawai‘i Forages

There are many factors that determine the concentration of copper in the forages available to the grazing animal. These include the soils they grow on; the type, quantity and relative abundance of the forages in the pasture; and the weather. Hawai‘i's soils vary widely in their relative fertility and copper availability depending on what parent material they are derived from, the prevailing climate and vegetation of the area, the topography of the landscape, and ultimately, the length of time since formation. Copper availability for plant uptake is reduced in soils that are leached and coarse textured or that are high in pH, organic matter, clay mineral, or oxide content. It is also reduced when concentrations of other minerals like iron, zinc, or phosphorus are high in the soil solution. Consequently, similar forages grown on different soils can vary in copper concentration (Suttle 2010).

Typically, copper concentration of forages can range from 3 to 15 ppm depending on the forage type (NRC 2016). Legumes tend to have a greater copper concentration than grasses; however, it is variable across species (NRC 2016). The concentration of copper in Hawai‘i forages can vary seasonally, as can that of the major antagonists, iron, molybdenum, and sulfur (Table 3), as a function of weather conditions that affect soil moisture. These fluctuations in forage concentrations of copper and iron may result in both primary and secondary copper deficiencies (Table 3; Thorne et al 2018). For example, Thorne et al. (2018) found that forage copper concentrations varied between 6 and 18 ppm, while iron levels averaged between 150 and over 700 ppm across the year in southern Hawai‘i island pastures (Figure 6). Based on copper and iron concentrations alone, a primary copper deficiency occurred in only one of 12 months, but secondary deficiencies occurred in five of 12 months when iron exceeded 200 ppm. These results show that copper status of the forages is not constant between pastures nor over time, and consequently, the copper status of the herd will likewise not be constant without sufficient supplementation. Collecting forage samples seasonally across all pastures will provide a copper (and other mineral) profile of forages on the ranch. This will help in developing or improving an effective mineral supplementation program that mitigates those periods of primary or secondary copper deficiency.

Evaluating Copper in Pastures

The first step to developing a mineral program for copper is to determine the nutritional composition of the forages your cattle are consuming. The supplies needed to collect forage samples are clippers or a sickle, a bucket, paper bags, and a marker (Figure 7). The goal of forage sampling is to submit a sample that is representative of the paddock in question. It is recommended to take 10

Table 3. The concentrations of copper and its major antagonists, iron, molybdenum, and sulfur, in Hawai‘i forages vary seasonally as a function of weather conditions affecting soil moisture.

	Season	Sample Size	DM %	CP %	Fe ppm	Cu ppm	Mo ppm	S %	Cu:Mo
Oct.–Nov. 2011	Fall	n=9	23.0 ±2.1	15.3 ±2.3	458.0 ±327.3	8.9 ±0.8	0.3 ±0.1	0.2 ±0.0	69.6 ±33.7
Dec. 2011–Feb. 2012	Winter	n=9	24.1 ±6.7	20.4 ±2.6	492.7 ±298.0	11.2 ±1.4	0.9 ±0.3	0.2 ±0.1	13.4 ±3.1
March–May 2012	Spring	n=6	28.8 ±1.7	20.1 ±1.7	810.8 ±855.3	10.5 ±1.9	0.5 ±0.3	0.3 ±0.1	29.0 ±20.61
June–Aug. 2012	Summer	n=9	23.8 ±5.2	18.9 ±1.1	201.7 ±77.9	11.3 ±1.3	0.1 ±0.0	0.2 ±0.0	111.11 ±12.69

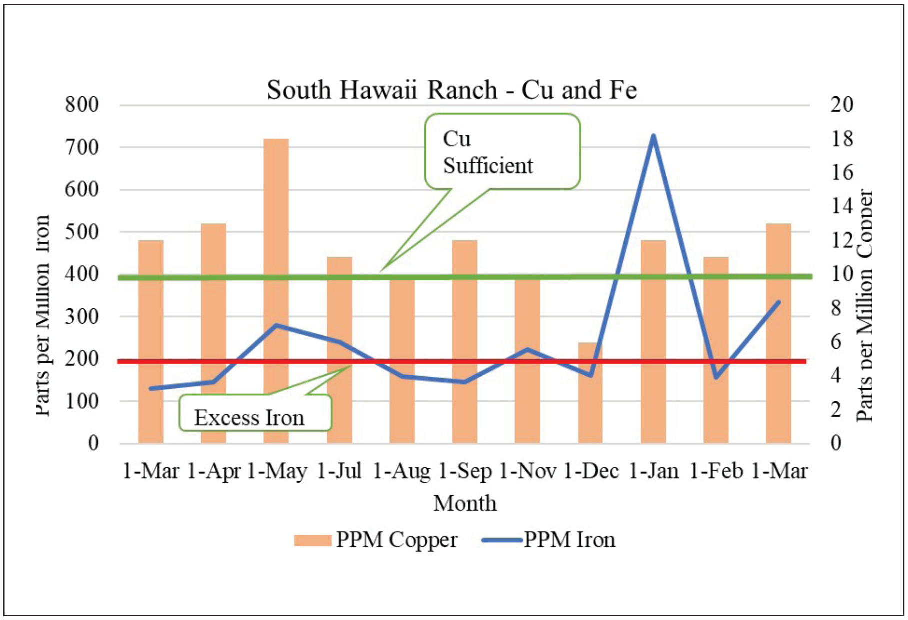


Figure 6. Changes in forage copper (Cu) and iron (Fe) concentrations in parts per million (ppm) over one year on a southern Hawai‘i ranch. Copper varied from a low of 6 ppm (deficient) to a high of 18 ppm, while Fe concentrations fluctuated widely between 150 and over 700 ppm. Copper concentrations of 10 ppm (green line) are considered adequate for healthy cattle diets in the absence of antagonists like Fe. Iron concentrations greater than 200 ppm (red line) are considered to be antagonistic to Cu absorption in the rumen of beef cattle.

to 15 random forage samples for a 40-acre paddock using a grab method. Keep in mind that you need to fill a paper grocery bag about ¾ of the way, collecting just over a pound (wet weight) of forage, to have a sufficient sample for analysis. To do this, estimate at what height cattle graze to on your operation (typically, the top half or two-thirds of the plant), grab a handful of forage, and then clip or cut at the appropriate height (Figure 7). Avoid collecting forage samples down to the ground, as cattle don't typically graze that low and the lower third of the forage will skew your forage analysis. Additionally, avoid weeds, dry leaf matter, or other plant material that cattle do not consume. Combine "grab" samples in a bucket and mix to create a composite sample. If you are able, indicate the top three forage species in your sample as a reference. Samples should be dried before shipping to labs for analysis. To dry the forage sample, either leave the paper bag in a vehicle with the windows cracked to air dry or place on a pan in the oven and dry on warm (approximately 170°F) with the oven door slightly ajar overnight.

When submitting forages for analysis, be sure to have the samples analyzed for all minerals, not just copper, due to the interactions that occur between copper and its antagonists. Contact your local Cooperative Extension office with any questions regarding analysis and for a list of labs that are equipped to analyze forages from Hawai‘i.

Mineral Supplementation Strategies

If through observations, monitoring of herd health key indicators (GOLD), or blood or liver samples, you detect a copper deficiency, there are several strategies to mitigate the effects. It is first important that the herd be on some form of consistent mineral supplementation program, utilizing either a commercial complete mineral mix or an individual free-choice (or cafeteria style) program. In either case, consistency is key; you cannot put the animals on and off the program and expect them to perform at their potential. If the general mineral supplementation program does not fully correct the deficiency or the herd is already on such a program, then providing additional copper, when it is most needed, will be necessary.

Figure 7. Step-by-step example of forage sample collection process: a) supplies needed for sample collection: bucket, clippers or sickle, paper bags, marker; b) cut forages half or two-thirds of the way from the ground, or whatever level your animals graze to; c) only about a handful per sample is needed for a "grab" sample; d) combine multiple grab samples into a bucket, mix, and note predominant forage species; e) place samples on a tray and allow to dry completely.

Mineral supplements are available in a variety of delivery methods as well as mineral sources. Delivery methods include dry or loose mineral, salt-based blocks, molasses-based tubs, or injectable minerals. Minerals can be provided as a complete mix or can also be supplemented individually, depending on the needs and goals of your operation. Mineral sources are broadly categorized as inorganic (sulfates, chlorides, and oxides) and organic (chelates, proteinates, and polysaccharide complexes). Depending on forage levels of copper and other minerals, you can develop a mineral program that is suitable for your forages and cattle.

Developing a copper profile of pasture forages, as previously discussed, will help in determining the most effective timing and form of copper to supplement with. Options include offering, along with the normal mineral supplements, free choice copper sulfate ($CuSO_4$), chelated copper boluses, or using an injectable copper source. Each of these comes with different labor and financial costs that must be considered when choosing a strategy. However, the cost of providing additional copper in the face of chronic deficiency should not be a deterrent. Considering the negative effects of copper deficiency on herd health, growth, and performance, and consequently ranch profits, providing additional copper will, in most cases, pay for itself.

Literature Cited

Boermans, H.J. 2010. Molybdenum poisoning. In: The Merck Veterinary Manual, 10th edition; Kahn C. M. and S. Line, eds. Merck & Co., Inc. Whitehouse Station, N.J.

Enjalbert, F., P. Lebreton, and O. Salat. 2006. Effects of copper, zinc, and selenium status on performance and health in commercial dairy and beef herds: retrospective study. *J. Anim. Physiol. Anim. Nutr.* 90:459–466. doi:10.1111/j.1439-0396.2006.00627.x

Garcia, J.D., M.M. Cuesta, R.S. Pedroso, M.P. Gutierrez, A.T. Mollineda, and J.R. Figueredo. 2006. Effect of copper on the reproduction of dairy heifers of Cuba. *Rev MVZ Cordoba*. 11:790–798.

Gengelbach, G.P., J.D. Ward, and J.W. Spears. 1994. Effect of dietary copper, iron, and molybdenum on growth and copper status of beef cows and calves. *J. Anim. Sci*. 72:2722–2727.

Gould, L., and N.R. Kendell. 2011. Role of the rumen in copper and thiomolybdate absorption. *Nutr. Res. Rev*. 24:176–182 doi: 10.1017/S0954422411000059

Maas, J. 2007. Methods to prevent copper deficiency in beef cattle. *California Cattlemen's Magazine*. October 2007.

McDowell, L.R. 2003. Minerals in animal and human nutrition. 2nd ed. Elsevier Science, Amsterdam, The Netherlands.

NRC. 2016. Nutrient Requirements of Beef Cattle. 8th rev. ed. Natl. Acad. Press, Washington, DC. doi: https://doi.org/10.17226/19014

Sakhaee, E. and S. Kazeminia. 2011. Relationship between liver and blood plasma copper level and abortion in cattle. *Comp. Clin. Pathol*. 20:467-469.

doi: 10.1007/s00580-010-1020-7.

Stabel, J.R., J. W. Spears, and T. T. Brown, Jr. 1993. Effect of copper deficiency on tissue, blood characteristics and immune function of calves challenged with infections bovine rhinotracheitis virus and *Pasteurella haemolytica*. *J. Anim. Sci*. 71:1247–1255.

Suttle, N.F. 1991. The interactions between copper, molybdenum, and sulphur in ruminant nutrition. *Annu. Rev. Nutr.* 11:121–140.

Suttle, N.F. 2010. Copper. In: Mineral nutrition of livestock. 4th ed. CABI, Cambridge, MA.

Thorne, M.S., J.P. Hewlett, G.K. Fukumoto, M.A. Oshiro. 2018. Development of an individual free-choice mineral supplementation program for improved grazing management in Hawaii's rangelands. 71st Annual Meeting of the Society for Range Management, Sparks, Nevada. January 27–February 3, 2018.

Ward, J.D. and J.W. Spears. 1997. Long-term effects of consumption of low-copper diets with or without supplemental molybdenum on copper status, performance, and carcass characteristics of cattle. *J. Anim. Sci*. 75:3057–2065.

Ward, J.D., G.P. Gengelbach, and J.W. Spears. 1997. The effects of copper deficiency with or without high dietary iron or molybdenum on immune function of cattle. *J. Anim. Sci*. 75: 1400–1408.

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