Color Plate 1. Fancy Blue Guppies in a 29 gal Tank.

Color Plate 2. Bluespotted Sunfish in a 45 gal Tank.

From: *http://dianawalstad.com*

Color Plate 3. Juvenile Cichlids in a 29 gal "Grow-out" Tank.

Color Plate 4. Small Tanks for Pet Shrimp.

From: *http://dianawalstad.com*

COLOR PLATES

Cover Picture. Rainbowfish in a 50 gal Tank. In the center are two males, a *Melanotaenia trifasciata* (reddish Goyder River strain) and a Turquoise Rainbowfish (*Melanotaenia lacustris*). I have kept Rainbowfish since 1988. I purchased my fish (as eggs or juveniles) from hobbyist breeders. Rainbowfish do not “color up” until adults of at least a year old, but they live 10-15 years. Mycobacteriosis (“Fish TB”) infected all of my Rainbowfish tanks in 2004 following the unquarantined addition of new fish to *one* tank. Several fish died. With the help of UV sterilizing filters, I got the disease under control without having to tear down the tanks. As of 2012, the majority of my Rainbowfish continue to do well.

Color Plate 1. Blue Guppies in a 29 gal Tank. I can catch guppies and their babies easily in this 29 gal planted tank where one end has potted plants on bricks (see Q&A on page 177). Blue guppies like these are hard to find, so I bred them myself. I crossed a store-bought male of brilliant iridescent blue coloring with a healthy female show guppy with a large delta tail. Like many of the imported guppies offered in stores, the male did not last long. I kept him alive *just* long enough (using a bare quarantine tank dosed with antibiotics) to impregnate the female guppy. Afterwards, I kept the female separated from all other males; her *second* batch of babies was from the desired mating. By selectively breeding offspring from the planned mating, I eventually got the fancy blue guppies depicted.

Color Plate 2. Bluespotted Sunfish in a 45 gal Tank. The Bluespotted Sunfish (*Enneacanthus gloriosus*) is a small, beautiful native fish found in ponds and lakes from New York to Florida. They are hardy, unaggressive, and get no bigger than 2-3 inches. Ideally, they should get live food. They will not eat flake food. However, I have maintained mine for several years feeding them mainly freeze dried bloodworms and small cichlid pellets. They will go wild for fresh earthworms.

Color Plate 3. Juvenile Cichlids in a 20 gal “Grow-out” Tank. For many years, I raised and sold Tanganyikan cichlids. They tend to be smaller and less aggressive than the Lake Malawi cichlids. I obtained juvenile fish from cichlid breeders listed with the American Cichlid Association. I consider the cost of the fish (about $5-$25 each) cheap considering the fact that the fish I obtained were consistently healthy (not one succumbed to disease) and of high quality. At times, I kept over a hundred juveniles in this tank with a small ‘hang-on-the back’ filter. Intense lighting and rapid emergent plant growth from the depicted Water Sprite (*Ceratopteris thalictroides*) kept the fish healthy with minimal maintenance.

Color Plate 4. Small Tanks for Pet Shrimp. I set up these two 2 gal tanks in 2009 using the Dry Start Method. That is, I grew the plants emersed for 10-11 weeks before adding water and the shrimp. As of 2012, the tanks and shrimp continue to do well. The Dry Start Method gives delicate plants a better chance to survive tank setup, which is always tricky. I describe the setup in my article ‘Small Planted Tanks for Pet Shrimp’.*

*Article can be downloaded free from the author’s website:
<http://www.dianawalstad.com>

Ecology of the Planted Aquarium

A Practical Manual and Scientific Treatise for the Home Aquarist

by

Diana Louise Walstad

Echinodorus Publishing, Chapel Hill, North Carolina (U.S.A.)

Ecology of the Planted Aquarium

A Practical Manual and Scientific Treatise for the Home Aquarist

by *Diana L. Walstad*

Published by:

Echinodorus Publishing
2303 Mt Sinai Rd.
Chapel Hill, NC 27514

Third Edition

Library of Congress Catalog Number 99-72828
Ecology of Aquarium Plants: a practical manual and scientific treatise for the home aquarist / by Diana L. Walstad

Includes table of contents, color plates, bibliographical references, and subject index
ISBN 978-0-9673773-6-0

1. Aquariums (about)
2. Aquariums- handbooks, manuals, etc
3. Aquarium plants
4. Aquatic plants
5. Ecology (in aquariums)

Printed in USA (BookMasters Inc of Ashland OH)

This book is dedicated to my parents Paul and Marjorie Walstad

Acknowledgements

Below is a list of scientists and professors who have helped me. They have taken the time from their busy schedules to review and comment on parts of the manuscript. Their ideas, comments, and critique have molded and reshaped many of my theories and helped keep the book 'on track'.

- Dave Huebert, Department of Botany, University of Manitoba (Canada)
- Elisabeth Gross, Limnology Institute, University Konstanz (Germany)
- Laura Serrano, Department of Ecology, University of Sevilla (Spain)
- Giovanni Aliotta, Dipartimento di Biologia Vegetale, Universita Degli Studi di Napoli Federico II (Naples, Italy)
- Wolfram Ullrich, Institute of Botany, Technische Hochschule Darmstadt (Germany)
- Dan Weber, NIEHS Marine and Freshwater Biomedical Core Center, University of Wisconsin (Milwaukee)
- David Spencer, Plant Biology Section, Aquatic Weed Control Research Laboratory, University of California (Davis)
- George Bowes, Department of Botany, University of Florida (Gainesville)
- Anthony Paradiso, Cystic Fibrosis Center, University of North Carolina (Chapel Hill)
- Claude E. Boyd, Department of Fisheries and Allied Aquacultures, Auburn University (AL)

During my 5-year tenure as Technical Advisor for the AGA (Aquatic Gardeners Association), I accumulated many Questions and Answers (Q&As). I have included many of those Q&As in the book and would like to thank AGA members for their permission to use them. I would also like to thank Neil Frank, previous editor of the AGA, who twice reviewed manuscript drafts of the book. His insightful comments helped.

To Robert G. Wetzel, Biology Professor and a leading authority on freshwater ecology, I owe special thanks. First, his comprehensive reference work (*Limnology*) prompted my initial search of the scientific literature on aquatic ecology. Second, his enthusiastic review of the first draft of *Ecology of the Planted Aquarium* convinced me that my book was worth the trouble.

The Second Edition was updated slightly from the First Edition. The main difference is that it includes the color plates.

TABLE OF CONTENTS

Chapter I.

INTRODUCTION

Ecology of the Planted Aquarium should appeal to hobbyists who wish to set up a successful planted aquarium plus understand more about its ecology.

Most aquarium plant books simply list/describe plant species or show how to set up a planted aquarium. This book is unique. For it explains the underlying mechanisms of the aquarium ecosystem– how plants affect the ecosystem and how the ecosystem affects the plants. It shows that plants are not just decorative but can also be quite useful in keeping fish healthy and reducing aquarium maintenance.

In addition, my book presents extensive scientific information that hobbyists have never seen. This information often contradicts prevailing ideas in the aquarium hobby– ideas that are often based on antiquated books and hobbyist observations rather than experimental data.

Aquatic plants studied include those from ponds, lakes, wetlands, and oceans. Many of the plants, such as *Vallisneria*, Hornwort, and *Cabomba*, are familiar to aquarium hobbyists. Others such as pondweeds and marine seagrasses may not be. However, aquatic plants, whether from the ocean or a tropical stream, have many of the same basic needs and physiology. Thus, concepts drawn from scientific studies of 'aquatic plants' can often be applied to 'aquarium plants'. In my opinion, any distinction between the two is obscured by the great diversity of species used by both aquarium hobbyists and aquatic botanists.

Although the book is directed toward aquarium keeping, many of the concepts apply equally to ornamental pond keeping. On occasion, I have noted where there might be differences.

In order to make the scientific studies more relevant to hobbyists, I have interspersed the text with typical or actual 'Questions and Answers' (Q & A). These Q & A, plus practical discussions at the end of chapters, show how the scientific information applies to hobbyists' aquariums. The last chapter describes how to keep aquariums that are inexpensive and simple to maintain.

The chapters of this book are grouped around the three goals of the book, which are to discuss: (1) how plants affect the aquarium ecosystem; (2) what factors affect plants; and (3) how hobbyists can use this information to maintain a successful home aquarium.

A. Chapters of the Book

1. Introduction

The introduction briefly describes the purpose and organization of the book and the characteristics of a 'healthy' aquarium.

2. Plants as Water Purifiers

In Chapter II the toxicity of water contaminants– heavy metals, ammonia, and nitrite– to fish and plants are discussed. I show how plants counteract those toxins to purify the water and protect fish.

3. Allelopathy

Allelopathy, defined as chemical interactions between organisms, is most likely rampant in home aquariums. I present scientific evidence for allelopathic interactions between aquatic plants, algae, bacteria, invertebrates, and fish. I list specific chemicals isolated from a variety of aquatic plants and then list the organisms these chemicals have been shown to inhibit. Finally, I speculate on how allelopathy affects aquarium keeping.

4. Bacteria

In Chapter IV, I classify different bacterial processes in terms of their positive and negative impacts on the aquarium. Topics include the generation of plant nutrients, CO_2, and humic substances by heterotrophic bacteria. In addition, I explain how bacterial processes both create and destroy aquarium toxins.

5. Sources of Plant Nutrients

Chapter V compares three potential sources of plant nutrients in aquariums– fishfood, a soil substrate, and tapwater. I use a model aquarium to quantify the theoretical contribution from each source. I show that fishfood contains all elements that plants require and that soil abundantly supplies most micronutrients. I compare hardwater versus softwater as a nutrient source. In the final analysis, I discuss which of the three sources best provides each nutrient.

6. Carbon

Carbon is briefly described in terms of alkalinity and water buffering, and then more thoroughly as a plant nutrient. I show that the element carbon often limits the growth of submerged plants both in nature and in aquariums. I describe strategies that aquatic plants use to obtain carbon. Finally, I show how hobbyists can help provide their aquarium plants with more CO_2.

7. Plant Nutrition and Ecology

Chapter VII describes the fundamentals of aquatic plant nutrition. Thus, the required elements and their chemical (nutrient) form are listed, along with each element’s function. Substrate versus water uptake of nutrients is discussed. I show that aquatic plants prefer ammonium over nitrates as their nitrogen source and why this makes biological filtration less critical in aquariums with plants. I discuss how the water chemistry of a plant's natural habitat influences its nutrient requirements.

8. Substrates

Most hobbyists do not have soil substrates in their aquariums, which may be the main reason they have trouble growing plants. For a better understanding of this critical topic, Chapter VIII discusses the general nature of soils before delving into the even greater complexities of submerged soils. Finally, it describes how hobbyists can use soils in the aquarium effectively.

9. The Aerial Advantage

In Chapter IX, I discuss the major problems that submerged aquatic plants face and why emergent plants do so much better. For the hobbyist, I describe how to promote aerial growth to optimize the aquarium ecosystem.

10. Algae Control

Chapter X focuses on a major problem that many aquarium hobbyists have– tanks overrun by algae. Common methods that hobbyists use to counteract algal problems are evaluated. I then discuss additional factors that the hobbyist can use to control algae. I show how hobbyists can successfully rid their tanks of algae without destroying the ecosystem.

11. Practical Aquarium Setup and Maintenance

In my opinion, planted aquariums are much easier to maintain than those without plants. Plants control alga growth and keep the tank healthy for fish without the drudgery of frequent water changes and gravel cleaning. In Chapter XI, I describe how I set up my planted tanks, which are both inexpensive and easily maintained. I also present my own guidelines as to fish, lighting, substrates, filtration, etc that the hobbyist can use to set up similar tanks.

B. Is the 'Balanced Aquarium' Dead?

Older aquarium books advocated the “Balanced Aquarium” in which plants and fish balance each others needs. Intrinsic to the idea of the balanced aquarium was the healthy growth of plants, but many hobbyists found planted aquariums difficult to maintain. Poor plant growth and unrestricted algal growth were persistent problems. Thus over the years, the idea of having a natural, planted aquarium lost its original appeal [1]. Many hobbyists gave up on the idea and dispensed with live plants altogether.

Furthermore, many aquarium hobbyists and retailers have little interest in plants, being primarily interested in keeping and breeding fish. Often the methods they use and recommend are not conducive to growing plants. For example, optimal fishkeeping without plants often depends on enhanced biological filtration, strong aeration, undergravel filters, and frequent tank cleaning. Beginning hobbyists that try to adapt these methods to growing plants in their aquariums often fail.

Other hobbyists, mainly from Europe and within the last 20 years, developed techniques for growing plants in the aquarium that were highly successful. The sophisticated technology they used consistently produced beautiful, planted aquariums, which I will call ‘High-tech’ aquariums. The end result did, indeed, resemble 'a slice of nature'. Unfortunately, the artificial methods to obtain such an aquarium ignored many of the natural processes of bacteria and plants. The end result– healthy fish and plants– resembled the natural, balanced aquarium, but the means to obtain it were unnatural, expensive, and laborious.[1]

With this book, I would like to resurrect the older version of the natural, planted aquarium but with a much greater understanding of how it works.

C. Characteristics of a Natural, 'Low-tech' Aquarium

The 'Low-tech' aquariums that I maintain are characterized by a small or moderate number of fish, reduced filtration and cleaning, a large number of healthy growing plants, and diverse microorganisms. Essential to my natural aquarium is moderate lighting, a substrate enriched with ordinary soil, and well-adapted plants. It differs from what many hobbyists are familiar with– dimly lit tanks with gravel substrates.

At the same time, it differs from the High-tech tank in that it takes greater advantage of natural processes. The Low-tech aquarium is easier (and much less expensive) to set up and maintain. This is because natural processes are taken full advantage of. For example, bacteria and fish– not artificial CO_2 injection– provide CO_2 to plants. Plants and soil bacteria– not trickle filters– remove ammonia from the water and protect fish. Fishfood and soil– not micronutrient fertilizers– provide trace elements to plants.

What are some specific characteristics of Low-tech aquariums?

1. pH Remains Stable

One criterion to gauge an aquarium's success is a stable pH; acid-generating reactions in the tank are matched by base-generating reactions. Tanks with water that become acidic over time are unbalanced, usually due to excessive

Q. I use a pH adjuster (containing dibasic phosphate) to keep the pH up, because the water constantly tends to acidify. The plants aren't growing as well as I would like. Do you think the phosphates in the pH adjuster will encourage algae?

A. They might, but the bigger problem is that your tank is going acid over time. In many aquariums, nitrification in the filters is the source of the acidity. In ‘fish only’ tanks it can’t be helped, but in planted tanks photosynthesis, denitrification, and other powerful acid-neutralizing processes keep the pH up.

The only tanks I have had “go acid” are those with poor plant growth, or those without soil in the substrate. Normally, my planted tanks show a neutral or alkaline pH. Base-generating reactions counteract acid-generating reactions. I would work on encouraging total plant growth in your tank.

[1]High-tech aquariums are sponsored by the two European manufacturers Dupla and Dennerle. The complete systems, which require metal halide lighting, CO_2 injection with automatic pH regulation, trickle filters, daily plant fertilization, and substrate heating cables [2,3], are quite expensive. For example, two hobbyists [4] report that the set-up for their 90 gal 'Super Show Tank' based on the Dupla system cost more than $3,500.

nitrification in the filter. **Table I-1** lists the biological and physical processes that affect the pH in aquariums.

Table I-1. Major Processes that Affect Aquarium pH.

Acid-Generating Processes (pH goes down)	**Base-Generating Processes** (pH goes up)
Respiration of fish	Photosynthesis by plants and algae
Nitrification by filter bacteria	Denitrification by bacteria
Bacterial metabolism (e.g. decomposition of organic matter)	Water and air mixing (loss of CO_2)

2. Low Maintenance

The hallmark of a Low-tech aquarium is that it is easily maintained. Aquariums seem to do well without hobbyist adjustment, maintenance, and cleaning. For example, my own aquariums often go for six months or more without water changes. Fish get fed well, so that plants do not need to be fertilized artificially. The only routine maintenance is replacing evaporated water and pruning excess plant growth. Tanks that are unbalanced need constant cleaning and adjustment.

3. Fish Behavior is Normal

Normal fish behavior is a good indicator of a healthy, balanced ecosystem. In tanks, this means that vigorous fish like Rainbows and cichlids should be thrashing over food at meals. Male guppies should be actively courting female guppies.

Abnormal fish behavior (not eating) or an inability to reproduce often indicates contaminated water. For example, otherwise vigorous fish will stop eating when water nitrite levels get too high.

D. How Plants Benefit Aquariums

Below are the benefits that plants– given a chance– play in the aquarium:

1. *Protect fish by removing ammonia.* Plants readily take up ammonia, which is toxic, even though there may be adequate nitrogen in the substrate or plentiful nitrates in the water. This is because aquatic plants have a decided and overriding preference for ammonia (see pages 107-108).

2. *Protect fish by removing metals from the water.* Heavy metals may or may not directly kill fish, but they can inhibit reproduction and suppress normal appetite, such that the fish eventually succumb to disease. Plants rapidly take up large quantities of 'heavy metals' like lead, cadmium, copper, and zinc from the water. Also, plant decomposition produces humic substances, which bind and detoxify metals (see pages 14-16).

3. *Control algae.* Good plant growth seems to inhibit algae, whether in nature or aquariums. How plants do this is not certain. However, plants produce and release a wide

variety of allelochemicals that are mildly toxic to algae (see pages 41-43). Plants also readily remove iron from water, thereby depriving algae of an important nutrient (see pages 167-170).

4. *Stabilize the pH.* Photosynthesis is a major acid-consuming reaction. Thus, vigorous plant growth keeps the water from becoming acidic over time.

5. *Increase biological activity within the tank.* Most microorganisms (bacteria, protozoa, fungi, algae, etc) do not live freely in the water but live attached to surfaces. Plants, especially the roots of floating plants, provide an ideal home for numerous microorganisms (see page 153), many of which recycle nutrients and stabilize the aquarium ecosystem.

6. *Oxygenate the water.* Actually, the air probably provides more oxygen consistently to fish than plant photosynthesis. And while it is true that plants also consume oxygen (plants 'breathe' just as humans do), healthy plants give off far more oxygen via photosynthesis than they consume by respiration. Even when plants are not photosynthesizing, such as at night, they probably remove less oxygen than one would expect. This is because they prefer to use the oxygen stored in their tissues rather than take up oxygen from the water. [2]

Q. My Black Moor has been sick for the last two weeks. It seems to be losing its scales and has white stringy stuff on its body. Its body is now gray-colored, instead of its original dark brown color. I keep the Moor in a small 2 gal tank with no plants, but it has a small box filter and I do 10-20% water changes every week.

I have another tank, a 10 gal with heavy plant growth with many red swordtails (including babies) that are doing fine. Should I try antibiotics?

A. Poor aquarium conditions may have lowered your fish's immunity to natural bacteria. Antibiotics might cure the immediate infection, but they won't help much to counteract the underlying problem-- a toxic substrate, contaminated water, etc. I would either clean the tank or transfer the Black Moor to the planted tank.

Results: I put the Moor into the planted tank. Within 2 weeks his problems cleared up. He is now eating all the snails in the tank!

Analysis: I am delighted to hear that your Black Moor has regained his health. Plants in the aquarium are much more than decoration or hiding places for fry. They protect fish by improving water quality (e.g., counteracting heavy metal and ammonia toxicity, removing excess CO_2, oxygenating the water, etc).

7. *Remove CO_2 from the water.* Excess CO_2– as much as oxygen depletion– can cause respiratory distress in fish (fish gasping at the surface [6]). Normally, plants would be expected to remove all CO_2 from the water during daylight hours.

8. *Prevent substrates from becoming toxic.* In my experience, a substrate that supports good plant growth doesn't become toxic, and it rarely (if ever) needs to be vacuumed. Plant roots keep it healthy (see page 135-136).

[2]During photosynthesis, oxygen accumulates rapidly within the plant lacunae, which are huge gas storage chambers making up about 70% of the plant's interior. This internal oxygen is used for the plant's respiration both day and night [5].

E. Promoting Plant Growth in the Aquarium

Many hobbyists would like to keep plants in their aquariums, but repeated failures or the expense of the High-tech systems has discouraged them. Thus, the rest of the book addresses the factors that affect plant growth in the aquarium. They are:

1. Nutrients. Tapwater, a soil substrate, and fishfood can easily provide all nutrients required by aquarium plants (see Ch V ‘Sources of Plant Nutrients’).

2. Algae Control. Plants cannot grow if algae smother them. Practical strategies, both short-term and long-term, for controlling algae are discussed in Ch X 'Algae Control'.

3. Fertile substrates. Theoretically, aquatic plants can get all nutrients from the water, so what's wrong with a gravel substrate? However, in practice, gravel substrates do not work very well. Plants need a fertile substrate to grow well and compete with algae. (See Ch VIII ‘Substrates’.)

4. Bacteria. Bacteria break down organic matter into CO_2 and other nutrients that plants can use. The complex and interesting role bacteria play in aquarium ecology are described not just in Ch IV (‘Bacteria’) but throughout the book.

5. Aerial (Emergent) Growth. Plants that access air for light and CO_2 grow much better than fully submerged plants (Ch IX 'The Aerial Advantage'). By using floating plants and encouraging other forms of aerial growth, hobbyists can increase total plant growth in the aquarium.

6. Light. Adequate light is essential for growing plants. In Ch XI (‘Practical Aquarium Setup and Maintenance’), I discuss the lighting needs of plants.

7. Plant Species. Different plant species may respond differently to individual tank conditions, such as lighting, substrate, water chemistry, CO_2, and other plant species in the tank. New tanks that are set up with a wide variety of species have a better chance to do well.

REFERENCES

1. Atz JW. 1952. The balanced aquarium myth. In: Axelrod HR (Ed.). Tropical Fish as a Hobby. McGraw-Hill (New York), pp 215-227.
2. Horst K and Kipper HE. 1986. The Optimum Aquarium. AD aquadocumenta Verlag GmbH (Bielefeld, Germany).
3. Dennerle L and Lilge H. *System for a Problem-Free Aquarium*. Dennerle GmbH (Germany).
4. Booth G and Booth K. 1993. Some assembly required (Pt 8). The Aquatic Gardener 6(4): 109-116.
5. Wetzel RG. 1983. Limnology (Second Ed.). Saunders College Publishing (Philadelphia, PA), p. 529.
6. Reid SG *et al*. 2000. Cardiovascular and respiratory reflexes in the tropical fish traira (*Hoplias malabaricus*): CO_2/pH chemoresponses. Respiration Physiology 120: 47-59.

Chapter II.

PLANTS AS WATER PURIFIERS

Aquatic plants protect fish from toxic ammonia, nitrite, and heavy metals. Intrinsic to the idea of plants as water purifiers are three facts:

1. Aquatic plants readily take up heavy metals
2. Humic substances from decomposed plant tissue detoxify heavy metals
3. Aquatic plants readily take up ammonia and nitrites

A. Heavy Metals

'Heavy metals' are toxic to all organisms, whether they are required micronutrients (zinc, copper, iron, manganese, nickel) or environmental pollutants (aluminum, lead, mercury, cadmium, etc).[1] **Table II-1**, which ranks several heavy metals according to their molar toxicity to various organisms, shows that mercury and copper are the most toxic.

Table II-1. Toxicity of Heavy Metals to Organisms [3].

Organism	High Toxicity ⇒ Low Toxicity
Algae	Hg > Cu > Cd > Fe > Cr > Zn > Co > Mn
Fungi	Hg > Cu > Cd > Cr > Ni > Pb > Co > Zn > Fe
Fish	Hg > Cu > Pb > Cd > Al > Zn > Ni > Cr > Co > Mn
Flowering Plants	Hg > Pb > Cu > Cd > Cr > Ni > Zn

Abbreviations: Al = aluminum; Cd = cadmium; Co = cobalt; Cr = chromium; Cu = copper; Fe = iron; Hg = mercury; Mn = manganese; Ni = nicklel; Pb = lead; and Zn = zinc.

1. Metals in Our Water Supplies

Which heavy metals in tapwater might be a problem for our fish? If human standards were the same as fish standards, water good enough for human drinking would be good enough for fish. However, this is not the case, especially for zinc and copper. First, fish

---

[1]Heavy metals, except for aluminum, are classified as 'Borderline' and 'Class B' metals. In contrast, calcium and magnesium are 'Class A' metals and are generally not toxic [1,2].

standards are much higher than those for humans (**Table II-2**). For example, fish require that Cu levels be 65 times lower (0.02 ppm versus 1.3 ppm) and Zn levels 50 times lower (0.1 ppm versus 5.0 ppm). Second, Cu and Zn are considered to be non-toxic to humans. Their standards are set for aesthetic reasons (taste, porcelain staining, etc) and are not federally enforced. This means that drinking water could conceivably contain enough copper and/or zinc to harm fish.

Table II-2. Some Heavy Metal Standards for Humans and Fish [4,5].

Metal	**Humans** (ppm)	**Fish** (ppm)
Cadmium	0.005	0.01
Chromium	0.1	0.05
Copper	1.3	0.02
Lead	0.015	0.1
Mercury	0.002	0.01
Zinc	5.0	0.1

Q. I am concerned with your conclusion regarding the extent of metal contamination in aquariums. It is unlikely that most municipal water systems would contain enough metals to seriously harm aquatic life; the only other source of metal contamination is from pipes.

A. I am not convinced. Hobbyists blithely add copper to their tanks to control algae and parasites with no idea of how toxic copper can be. Both zinc and copper could be in drinking water at levels that could be toxic to fish. My own well water has enough zinc to kill invertebrates in my aquariums and keep brine shrimp eggs from hatching (see page 183). A few hobbyists have reported problems from excessive copper in municipal tapwater. Other hobbyists might not even recognize problems from metal toxicity. (Sick fish, poor hatches from brine shrimp eggs, dead invertebrates, and plant meltdowns are so easily attributed to other causes.)

Metal toxicity has rarely been discussed in the aquarium literature. This interesting topic, which is related to micronutrient nutrition in plants, fish physiology, and decompositional processes in aquariums, deserves some attention.

Municipal water treatment procedures such as coagulation-flocculation and lime softening help remove Zn and Cu. Thus, metal contamination of city water would seem unlikely. However, high copper levels have been reported in certain areas. For example, several Connecticut towns (Bridgeport, Hawkstone, Norfolk, etc) in 1997 reported 'high-risk' areas with Cu levels ranging from 0.14 to 1.1 ppm. And one hobbyists from Massachusettes has reported aquarium problems arising from Cu levels in the city water that fluctuate from 0.5 to as high as 2 ppm.

Ground water, especially water from private wells, could also contain harmful

Q. Surely, if the water is safe for humans to drink, it must be okay for the fish?

A. We humans don't live and breathe in water, so our dosage is small. Furthermore, much of the metals that enter our digestive tract would be inactivated by binding to organic matter (partially digested food).

In contrast, fish gills and skin are directly exposed to whatever metals are in the water. Heavy metals 'sneak in' through pathways designed for nutrient uptake, particularly calcium. Thus, in metal-contaminated water, the fish will contain high metal levels-- and be injured accordingly.

levels of zinc and copper. Indeed, one survey [6] of U.S. ground water shows huge variations in both Cu (0.01 to 2.8 ppm) and Zn (0.1 to 240 ppm). Additional heavy metal contamination of drinking water may come from the leaching of metal pipes, heating coils, and storage tanks.

2. Mechanisms of Heavy Metal Toxicity

Many metals are toxic, because they capriciously bind to organic molecules within organisms. For example, mercury binds to the sulphydryl groups (-SH) found on virtually all proteins, thereby inactivating the proteins and their cellular functions.

Iron toxicity occurs in plants as well as humans (e.g., hemophiliac patients overloaded with iron from continuous blood transfusions [7,8]). The toxicity occurs when cellular oxidation of iron (Fe^{2+}) produces highly reactive oxygen radicals, which can kill cells by destroying DNA, membrane lipids, and proteins.

However, the most common mechanism of metal toxicity is when a foreign metal displaces another metal from its specific binding site on organic molecules. For example, nickel can displace zinc from its proper binding site on the enzyme carbonic anhydrase thereby inactivating the enzyme [1]. (Many enzymes require the attachment of a specific metal in order to function.)

Heavy metal substitution for calcium is often an underlying factor in metal toxicity. All cell membranes have a phospholipid bilayer that is stabilized by Ca. Intruding heavy metals can displace the desired Ca and disrupt cell membrane structure and function [1]. And calcium's unique role as a secondary messenger in cells insures that many functions of almost any organism are susceptible to metal toxicity [9,10].

3. Metal Toxicity in Fish

While high levels of heavy metals can cause gross tissue damage and death in fish [11], the most common effects (behavioral changes and reproductive failure) are from minor contamination. Behavioral changes result when heavy metals disrupt the release of neurotransmitters and hormones from producing cells [12].

Fish had problems capturing live daphnia following a 4 week exposure to lead (**Table II-3**). Control (untreated) fish reacted to the daphnia much further away than Pb-exposed fish. Also, lead accumulated in the brains of Pb-exposed fish.

Table II-3. Effect of Lead (Pb) on Feeding in Minnows [17].

Variable	**Controls** (no lead)	**Lead Exposure**	
		0.5 mg/l	1.0 mg/l
Reaction distance (cm)	2.7	1.9	1.7
Miscues during feeding (number of)	9.0	50	49
Time to consume 20 daphnia (min)	1.4	6.2	5.5
Pb in fish brain (mg/l)	Not detected	0.45	0.82

Low levels of heavy metals may affect normal fish behavior such as schooling, feeding, swimming, and successful spawning. For example, copper was shown to significantly reduce the swimming performance of rainbow trout [13]. Continuous exposure to aluminum decreased the appetite and growth rate of young trout [14]. Lead had no effect on the growth of young male trout, but it profoundly affected sperm production [15]. Copper was shown to impair the smell receptors of salmon, which are critical to its spawning migration [16].

Fish are guided by their own unique circadian rhythms, which are controlled by neurotransmitter levels within specific regions of the fish brain. By disrupting neurotransmitter function, heavy metals can affect the natural circadian rhythm of fish [12]. For example, when sea catfish were exposed to 0.1 ppm copper, they lost their normal circadian rhythm and became hyperactive (**Fig. II-1**). That is, treated catfish were more active both day and night, whereas untreated (control) catfish were much less active during the day, especially in the afternoon.

Fish are most sensitive to heavy metals during their developmental stages. Thus, while a particular metal concentration might be safe for adult fish, it could injure fish during a critical development phase. For example, the yolk sac membrane (chorion) was very fragile and easily ruptured in embryos exposed to just 0.3 ppm of zinc [19].

Table II-4 shows standards for seven heavy metals on various freshwater fish. These standards, which are based on the sensitivity of developing fish, are much more stringent than the general standards listed earlier in Table II-2.

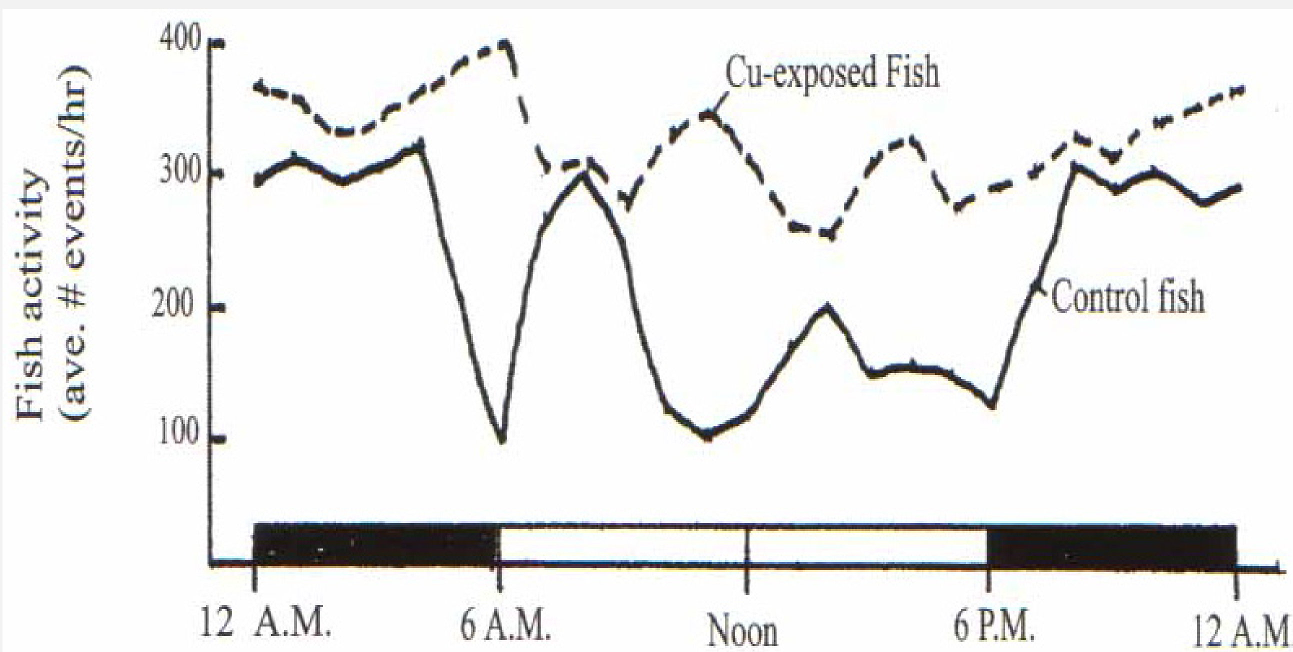

Figure II-1. Diel Activity of Sea Catfish as Affected by Copper. Sea catfish were exposed to 0.1 mg/l of Cu for 3 days and then monitored for activity over a 24 h measurement period. Activity was determined when fish tripped a photodiode as they moved between compartments.

(Fig. 1 from Steele [18] redrawn and used with kind permission from Kluwer Academic Publishers.)

4. Metal Toxicity in Plants

Plants afflicted with metal toxicity exhibit various symptoms that might be interpreted incorrectly as nutrient deficiencies. Symptoms of aluminum toxicity for *Vallisneria* are premature browning and senescence of leaf tips [22]. Excesses of either copper, manganese, or zinc can induce iron deficiency and chlorosis [23].

Iron toxicity has been studied in at least two aquatic plant species. Investigators [24] reported a 75% growth reduction in the pondweed *Potamogeton pectinatus* after adding iron (1.2 mg $FeCl_3$/g) to the substrate. Leaves turned brown. Roots turned pale or red brown in color, and root growth was stunted. *Hydrilla verticillata*, exposed to well water containing 1.2 ppm Fe, became covered with a rusty brown color and began to decay [25].

Q. I added iron (as $FeCl_3$) to my tank to reduce phosphates in the water. (Phosphate reacts with iron to form insoluble iron phosphate.) Six days afterwards, the phosphate concentration had decreased from 0.6 ppm to 0.1 ppm, but I began to see phosphate deficiency in some of my plants. It started with the slower growing plants. For example, the *Cryptocoryne* had brown spots on their leaves, which expanded until the whole leaf was affected. Fast-growing plants species seemed unaffected by the P deficiency, which surprised me, as these plants usually require more nutrients.

A. I think you're confusing phosphate deficiency with iron toxicity. Phosphate levels of 0.1 ppm in the water are more than sufficient for plant growth. The brown spotting of the leaves suggests iron toxicity. The browning is due to iron deposits in the leaves, as the plant tries to store the excessive iron coming in.

The fact that your faster growing plants did not show the 'deficiency' supports my contention that the problem is metal toxicity not nutrient deficiency. Metal toxicity in plants can be overcome by rapid growth. Faster growing plants 'dilute out' the problem; metal concentrations within the tissues decreases with new growth. Slow-growing plants are at a disadvantage; the metal concentration within the plant builds up to injurious levels.

Table II-4 Heavy Metal Standards for Sensitive Life Stages of Fish [19].

Metal	**Fish**	**Metal's Effect on:**	**Maximum Acceptable Concentration** (ppm or mg/l)
Cadmium	Flagfish	Spawning	0.004- 0.008
"	"	Juvenile mortality	0.003- 0.017
Copper	Brook Trout	Juvenile mortality	0.010- 0.017
Chromium	Brook Trout	Juvenile mortality	0.20- 0.35
Lead	Brook Trout	Juvenile deformity	0.058- 0.12
Mercury	Fathead Minnow	Juvenile growth	< 0.00026
Nickel	Fathead Minnow	Egg hatching	0.38- 0.73
Zinc	Flagfish	Growth	0.026- 1.2
"	Fathead Minnow	Egg fragility	0.078- 0.15