Freeze Damage in Woody Plants

by Andy Walsh

Introduction

This article is adapted from an Internet Bonsai Club post. In it, Andy discusses the physical and chemical changes involved when plant stems and roots freeze. This kind of information is crucial to constructing cold weather protection for many areas of the country. Some slight editing has been done to make it more readable in this context.

The Three Stages of Freezing

First off, several times here writers have stated that their trees are frozen in the winter and survive. It's clear to me that there is great misunderstanding around what some people think when they say a plant is frozen. If a plant truly freezes it dies. The formation of ice within the cells of a plant is invariably fatal. What I think many people see in winter is the soil of their trees frozen and they equate this with the plant being frozen. This is not the case.
From my readings, there are basically three stages of freezing that can be observed with, and have significance to, a Bonsai:

1. The freezing of the water in the Bonsai's soil.
2. The freezing of "inter"-cellular water in the plant's tissues.
3. The freezing of "intra"-cellular water in the plant's tissues.

Freezing of Water in the Soil

The freezing of the water in the soil occurs at the highest temperature of the three. Water in nature rarely freezes at its physical constant of 0C (32F) as there is always something dissolved in it that lowers the freezing point. However, since soil is primarily comprised of particles and (usually) not a lot of solute, water freezes at just a little below 0C. When ice forms in soil it actually comes out of the soil solution leaving particles and solutes behind (Ref. 2). Those of you in the colder areas who experience frost heaves will note that the ground has ice crystals on the soil surface. In many instances it is not the soil itself that is frozen (it is muddy underneath). However, this only occurs where there is room for the ice crystals to grow - namely the surface. In the ground, and in the soil of a Bonsai, the water has nowhere to go and freezes in place. I have seen the water in the soil of my Bonsai frozen like this for 19 winters.
(By the way, it has also been said here that this freezing puts serious and damaging pressure on the roots due to the expansion from the ice. However, plant cells have rigid cell walls and are capable of withstanding several atmospheres of pressure on a regular basis due to their own normal internal turgor pressure. Actually, ordinary land plants have been shown to survive hyrdostatic pressures of over 1000 atmospheres. The resistance to pressure stress varies seasonally and, believe it or not, has been shown to increase with cold hardening (Alexandrov 1964, in Ref. 2).
What is important to understand at this point is that the water in the soil is frozen and NOT the roots or the shoots of the Bonsai. Water freezing in the soil of a Bonsai is not a problem for the tree (except for what I mention later).

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At the freezing temperature of water in the soil, the tree has little worries; but as the temperature falls further, the roots and shoots of the tree are placed under greater risk. As the temperature gets lower the plant is in danger of freezing itself which as I said before is invariably fatal to the plant. Plants have several mechanisms by which they avoid freezing which are not completely understood yet.

One mechanism is the storage of solutes (sugars, sugar alcohols, proteins, etc.) within the cell protoplasm. The presence of solutes lowers the freezing point of water and keeps the plant from freezing if the temperature falls below 0C. In some cases this mechanism provides great protection. Japanese researchers (Ichiki and Yamaya in Ref. 2) found that Apples (Malus sp.) increase the level of sorbitol to over 30 times its pre-winter levels and correlated the degree of winter hardiness to the level of sorbitol in the tracheal sap. At peak sorbitol levels, hardiness was experimentally measured to as low as -25C. Interestingly, sorbitol levels varied throughout the season depending on the external temperature, that is, as the temperature fell the sorbitol levels increased and vice versa. This is true of many other species as well - but not all. (by the way, hardiness is not something that can be built into such trees ahead of time by special fertilizing routines. A quick cold snap following a warm spell can kill such a tree at temperatures well above that plant's lowest known hardiness level).

Freezing of Inter-Cellular Water

Another mechanism that plants use is the expulsion of water from the cell protoplasm into the inter-cellular spaces. Changes in cell membrane permeability allow water to leave the cell and enter the spaces between the cells and the water then freezes there instead of within the cell. This is the second stage of freezing that I mentioned above that can be observed by a Bonsai grower on his/her trees. In some trees when the temperature falls low enough (quite low) this phenomenon occurs and in the case of Pines can be seen by the grower. The needles of a Pine can seem like they are frozen as they are stiff and will crack when bent. The cells of the Pine needle have allowed water to "escape" into the intercellular spaces and it freezes there giving the needles the appearance that they are frozen. AGAIN, this is an appearance and the plant itself (living tissue) has not frozen. This mechanism also allows the "intra"-cellular water to avoid being frozen.

Freezing of Intra-Cellular Water

The third freezing stage is when the intra-cellular water freezes. This causes the death of the cells that do freeze and is shown to the Bonsai grower through the loss of branches or the tree itself come springtime. One freezing avoidance mechanism that is not clearly understood is what is called "supercooling". By some means, the cellular "sap" remains liquid at temperatures well below the known freezing point for that "sap". There is some physical relationship to the diameter of the vessels that this "sap" is in, since in larger vessels the "sap" does freeze at higher temperatures.

At this point I must say, [about the discussion of] "round" vs "sharp" ice crystals forming when there are sugars in solution, that I don't know that any such thing occurs. But it really is a moot point since intra-cellular ice formation, whether from "round" or "sharp" ice crystals, will be fatal to the cell. It matters not, what shape the ice is in. This is a cold hard fact. I will add though, that it is specifically ice [crystal] formation and not freezing that is believed to do the damage, as animal and plant cells can be quickly frozen in liquid nitrogen and have recoveries of in the greater than 90% range on thawing. This rapid freezing causes the intra-cellular water to freeze in-place without the formation of ice within the cells. This is successful only if the freezing process is taking place at a rate of =/> 1degree C/minute. However, plant cells were the least (by far) affected by the rate of the freezing process. (I was involved with the validation of several liquid nitrogen cell bank freezers a few years back, so I have some personal experience with this one).

Temperature Ranges of the Three Stages

Now, each one of these 3 freezing events takes place in a specific temperature range. Soil freezes first, "inter"-cellular water next, and "intra"-cellular water last. In the case of plant shoots (remember I said shoots; very important word) these temperature ranges could be something like:

1. 0 to -5C (32 to 23F) for soil water
2. -5 to -10C (23 to 14F) for "inter"-cellular water
3. -20 to -40C (-4 to -40F) for "intra"-cellular water.

These are arbitrary ranges for the sake of example and not specific to any particular species. However, such ranges would probably apply to many species in many temperate zones. Many of you will note that the winter temperatures for your area would not meet the "criteria" for "intra"-cellular freezing and hence your trees should be pretty safe in your area. That is indeed the case. What gives then with all this talk of winter protection for Bonsai?

What gives is that the hardiness values for various species that have been bandied about here of late ONLY apply to the above ground tissues. The root systems of plants do not undergo the same degree of hardening by any stretch of the imagination. This is where trees as Bonsai, and trees in nature part company. In nature, a tree's roots are below ground and are not subjected to anywhere near the widely varying and deeply cold temperatures that the above ground shoots are. They do cold harden somewhat; but not to a great degree. (by the way, if the trunk of a tree is buried under soil prior to the onset of the fall temperature drop, the tissues of the trunk under the soil will not cold harden like the rest of the above ground parts and will be easily damaged if exposed). When a tree is removed from the ground and placed in a pot, it's life can be placed in jeopardy since its roots can now see temperatures they never saw in nature. This is the very reason why winter protection of Bonsai is necessary. (Indeed if Bonsai were hardy to -40 etc. why would most of us even bother with winter storage?) Nothing in particular needs to be done to help the above ground parts make it through the winter; it is the below ground parts that need the help. I know of no special tricks other than avoidance of low temperatures to prevent freezing damage to roots.

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Methods of Protection

Such protection is typically accomplished by keeping the Bonsai in a temperature controlled greenhouse, by keeping the Bonsai in a coldframe, by placing the tree back in the ground, or by mulching around the pot (in order of decreasing effectiveness). All these actions can help prevent the root systems from reaching their "killing temperatures" and prevent root damage or death. When Bonsai people go to any of these various lengths in winter they are really protecting the roots of their trees from reaching their "killing temperatures". But many growers don't seem to know or appreciate that.

Killing Temperatures for Roots Vary by Species

The temperatures at which roots are killed, while directionally higher than those for shoots, also show wide variability from species to species. For example the "killing temperature" of mature roots for Magnolia stellata is only -5C (23F) whereas for Juniperus conferta it is -23C (-9.4F) (Ref. 5). In my experience, Trident Maples are very susceptible to moderately low temperatures while many other species, for instance Azaleas, are not. I have wintered cuttings of Azaleas outdoors on the ground with no mulching for many years and they have survived with no problems. Reiner [Goebel] wrote here that his collected Eastern White Cedars are not provided with any winter protection at all (keeps them on their benches in Canada) and do just fine. Both Azaleas and Eastern White Cedars have dense, fibrous and shallow roots systems and it is possible that their roots are normally exposed to colder temperatures and have greater resistance. I don't know whether their greater resistance is due to the roots surviving at lower temperatures or their greater ability to regrow in the spring.

Stem Tissue Dehydration

At this point it's important to return to the one other winter issue related to the freezing of soil water that I mentioned in the beginning of this post. I mentioned that the freezing of soil water is not a problem for the tree. It isn't, except under certain circumstances. If the temperature of above ground tissues rises substantially and the soil water remains frozen (as can occur in many greenhouses), transpiration of water can occur from the shoots. If the roots cannot obtain any water from the soil they cannot replace any that is lost from the shoots and the shoots can dessicate. This situation can be greatly aggravated by any wind which will help to drive transpiration losses. This can result in the "winter dieback" of shoots and branches. Obviously this situation is very undesirable. For Bonsai growers this is best avoided through some form of windbreak. Greenhouses and coldframes (or porches and garages) naturally supply this but trees planted in the ground or mulched may need (depending on the area) some form of windbreak placed around them for the greatest protection from this potential threat.

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In Summary

Now, let me try to pull all this "stuff" together into some useful summary that anyone, anywhere, can refer to and have the necessary information in hand to make informed and confident decisions on what they need to do for their Bonsai in winter.

1. Bonsai from temperate plants will enter a period of dormancy in fall which is triggered by shortening days and/or falling temperatures. Exposure to short days, low temperatures and (very importantly) frost induces the plant to begin "cold hardening" to sustain it from the coming winter temperatures.
2. Bonsai from temperate plants need to undergo a period of chilling in order to break this dormancy and start regrowth. This period has been defined as 1 to 10C (34 to 50F) for a period of 260 to >1000 hours (Ref. 4). In many cases these requirements are met by January (in the Northern hemisphere); however, the return of consistently warm temperatures is necessary for the plant to resume growth.
3. The above ground parts (shoots, leaves, buds) of Bonsai from most temperate plants (after "cold hardening") can withstand very low temperatures (some as low as -70C)
4. The roots of Bonsai from most temperate plants do not "cold harden" like the above ground parts and are much more sensitive to low temperatures and can be more easily damaged.
5. Freezing of the soil in a Bonsai pot is not necessarily a threat to the plant unless it is accompanied by prolonged periods where the shoots are at higher temperatures and/or exposed to drying winds and dessication of the shoots becomes an issue.

From these 5 points I believe it can probably be seen that the optimum winter handling of Bonsai from temperate plants are:

1. Allowing the plant to properly enter dormancy and "cold harden". Exposure to the first frosts of the fall are particularly important.
2. Storing the plant (remember optimally) well watered in an enclosed, temperature controlled area where the temperature is held at 1 to 10C (34 to 50F) throughout the winter to allow the appropriate temperature and time for dormancy to be broken, to keep the temperature from falling too low and damaging the roots, and to keep the soil from freezing to protect the shoots from dessication injury.
3. Removing the plants from this protected area when the temperature conditions for growth return.

Now obviously most people cannot attain step 2 easily. But attaining close to that should be the goal. There are a number of winter storage procedures that many people have shared here that will approximate this ideal. Coldframes, garages, porches, mulching (with a windbreak), burying the pot (with a windbreak), are all make-shift ways of coming close to providing the ideal winter protection.

And finally

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With the above ideal model in mind (and the reasons why) and knowledge of the typical winter conditions in your area I believe most readers will be able to confidently pick an effective winter storage scheme.

I hope this was helpful (and readable).

Andy

References:

1) Levitt, J. (1980) "Responses of Plants to Environmental Stresses". 2) Li, P.H. and A. Sakai (1978) "Plant Cold Hardiness and Freezing Stress". 3) Long, S.P. and F.I. Woodward (1987) "Plants and Temperature". 4) Moore, T.C. (1979) "Biochemistry and Physiology of Plant Hormones". 5) Whitcomb, C. (1984) "Plant Production in Containers".