FEATURES

Humidity in Horticulture[1]

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Humidity as related to horticulture is discussed in terms of: ways of expressing humidity levels; physical properties of water vapor; and temperature-humidity and air circulation-humidity interactions. The role of humidity in transpiration, killing freezes, and storage and transport of fruits and vegetables is discussed. Also given are sources of information on methods of recording and controlling humidity in postharvest applications.

Humidity affects all aspects of horticulture, yet it is all too often ignored, misunderstood, or misapplied. In preharvest horticulture, humidity is more a fact of life than a controllable variable, but its influence should always be considered. In postharvest horticulture, humidity is often a controllable variable that has assumed increasing importance in recent years (e.g. 2, 4, 13, 22). Nevertheless, the solution of problems involving humidity is often hampered either by inadequate comprehension of the essentials of humidity or, more often, by a lack of coordination in applying the disciplines of horticulture, physics, engineering, plant physiology, plant pathology and sometimes others such as meteorology or economics.

Here, we attempt to gather in one brief paper the major aspects of humidity as relating to horticulture. No attempt is made to survey all aspects of the literature relating to humidity in horticulture; instead, examples will be quoted to indicate both applications and something of the extent and depth of the literature available. No attempt will be made to cover the mechanics of the many ways of determining, recording, and controlling humidity. We will just examine what is meant by "humidity" and something of how it affects horticultural products.

Ways of expressing humidity

Humidity can be expressed in many different ways such as: percent relative humidity (% rh), specific humidity, dew point, vapor pressure, and various combinations of these. Each is useful, but considerable confusion often arises either due to misuse of terminology or due to authors in a particular discipline presuming that their usage is familiar to readers in other scientific disciplines.

However humidity is expressed, the observation on which it is based is most commonly the difference between dry-bulb and wet-bulb thermometer readings. In these the wet-bulb reading is depressed due to evaporative cooling and is directly related to both temperature and to the vapor pressure of water vapor in the air. This reading is only meaningful if the air velocity over the wet bulb exceeds 500 ft/min (ca. 150 m/min). At 1000 ft/min (ca. 300 m/min) error is within 1%, provided the wick on the wet bulb is wetted with distilled water and free of dirt and accumulated salts (14). Readings from wet- and dry-bulb thermometers in torpid or slowly moving air do not relate accurately to humidity levels. For accurate humidity measurement the two thermometers should be calibrated to fractions of degrees. Thermometers accurate to ± 1°F can result in up to ± 7% error in % rh.

Percent relative humidity (% rh). Love (12) has referred to percent as "the fertile mother of fallacy." Nowhere is this more apparent than in the frequent misuse of relative humidity values. Percent relative humidity is, in effect, a ratio between the quantity of water vapor present and the maximum possible at that temp and barometric pressure. (Even this is an over simplification, ignoring fine differences between definitions based on partial pressure and on percent saturation). It is important to note that it is incorrect to say ". . . the amount of moisture that would saturate the air." The water vapor and the air coexist independently. *Relative humidities can only be compared at the same temp and barometric pressure.*

Absolute (or specific) humidity[2]. This is the measure of the wt of water in a given wt of dry air. Engineers express this as grains (gr) (1/7000 lb.) of water per pound (lb.) of dry air. In metric measures, the equivalent is g of water per kg of dry air; one gr/lb. = 0.1428 g/kg. Fig. 1 shows a typical psychrometric chart in which absolute humidity is shown as a vertical axis on the right. Relative humidity appears as a series of curving lines separating widely as the dry bulb temp (on the abscissa) increases. Thus, atmospheres of similar % rh may have widely differing specific humidities if they are at different temp. This accounts for numerous examples of diffusion gradients occurring in directions that are sometimes unexpected. For example, (referring to Fig. 1A), in a cold storage running at 35°F and 100% rh, absolute humidity is 30 gr/lb. If the air outside is at 73°F and 50% rh, ambient specific humidity is 60 gr/lb. For those used to thinking only in terms of % rh, there is an apparent 2:1 moisture gradient from the storage room atmosphere outward toward the ambient conditions. In actual practice, there is a 2:1 moisture gradient from the ambient air *into* the storage.

The advantage of retaining absolute humidity as a concept in terms of actual weight of water vapor in the air is exemplified in the use of steam for humidification at various temp. At 32°F, only 6 gr of steam are necessary to raise 1 lb. of air from 60 to 90% rh. The heat load contributed by 6 gr (0.000857 lb.) of steam is negligible in most circumstances. However, 55 gr of steam per lb. dry air are necessary to raise relative humidity from 60 to 90% at 85°F (as in a Florida citrus degreening room) and this may contribute enough heat to make regulation at 85°F difficult.

Dewpoint (DP) is very commonly used as a measure of humidity, particularly in meteorology (15). DP is the temp to which moist air has to be lowered (at a constant pressure) in order to initiate condensation (100% rh). Once a given condition of temp and humidity is located on the psychrometric chart (Fig. 1), DP can be determined by moving horizontally to the left, being the temp at which the horizontal line intercepts the 100% rh curve. For example, at 85°F and 30% rh

[2]There is considerable variation in usage of such terms. Although the definitions given here are not in strict accord with those of ASHRAE (American Society of Heating, Refrigeration and Airconditioning Engineers), they are in common use and chosen as being most generally comprehensible to non-engineers.

[1]Received for publication January 6, 1975. Florida Agricultural Experiment Stations Journal Series No. 5845.

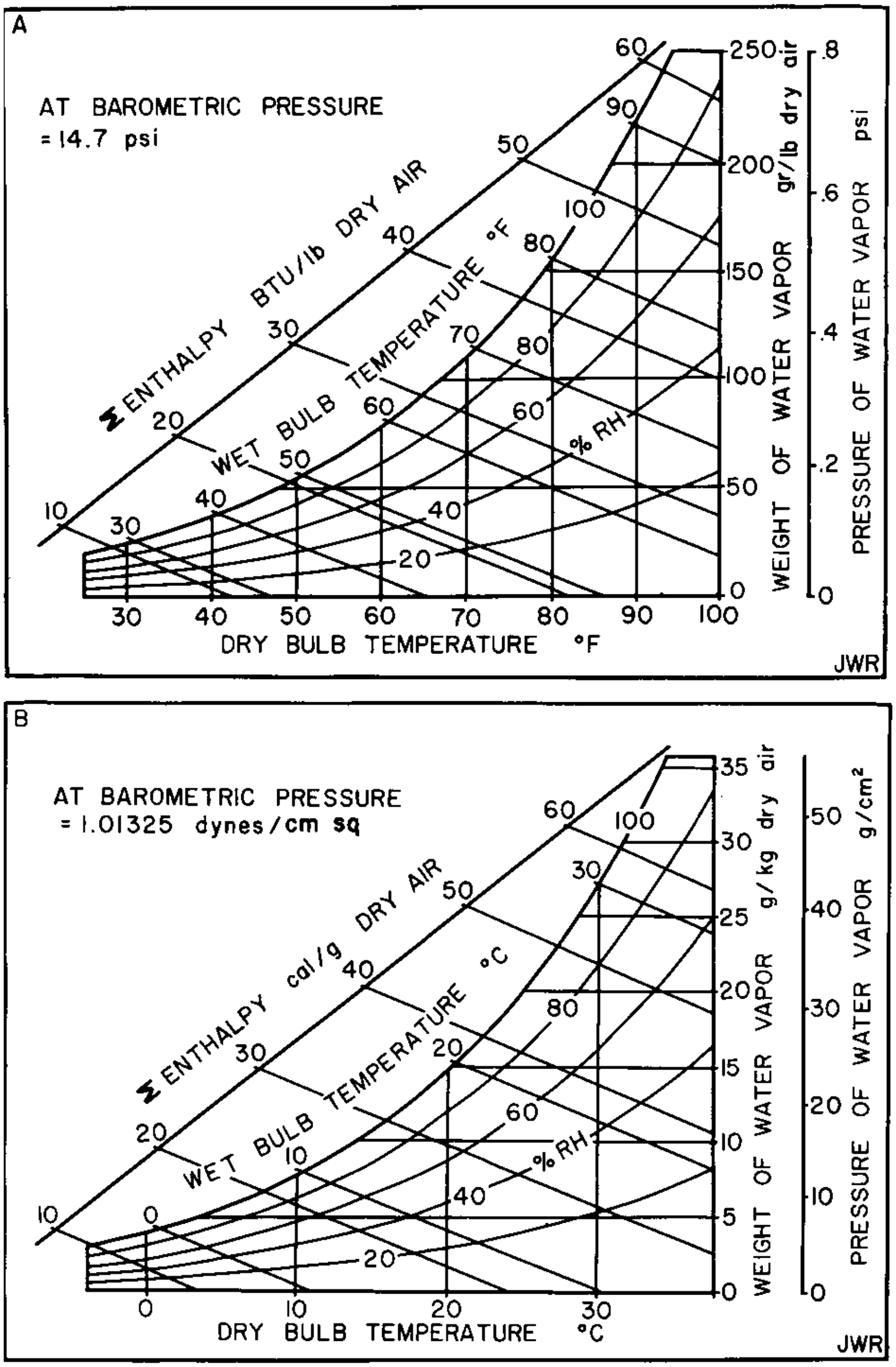

Fig. 1. Stylized psychrometric charts relating temp, humidity, and enthalpy (total heat) at normal sea level barometric pressure. *A* is in U.S. units. *B* is in metric units, still unusual for this use in North America. Dry bulb temp is on the abscissa. Absolute (specific) humidity and vapor pressure are on separate scales on the axis. Relative humidity is on the curved lines diverging with increasing temp. Wet-bulb temp is shown on the 100% rh margin. Enthalpy lines parallel those for wet-bulb temp since both depend on the temp of adiabatic saturation. The usual way to locate a given condition is by the intersection of the vertical line for dry-bulb temp and the sloping line for wet-bulb temp. Once a given condition is located, all other parameters can be read off the chart, including some (such as volume per unit mass) not shown here.

DP is 50°F.

Vapor pressure. In any dry air + water vapor combination, the water vapor exerts its own partial pressure. *At a given barometric pressure,* a direct correlation exists between absolute (specific) humidity and vapor pressure regardless of temp (Fig. 1). Vapor pressure is often used as an expression of humidity levels, particularly for humidity gradients which are often expressed in terms of "vapor pressure deficit" (vpd); i.e. the difference between vapor pressures at two points. The vpd determines rate of evaporation and hence of transpiration and so is a measure of genuine horticultural significance. Moreover, the kinetic implications of expressing such differences in terms of "pressure" is particularly attractive in teaching. However, vpd is comparative only, giving no indication of the amount of water vapor involved. For this reason, absolute (specific) humidity remains the most exact expression of humidity, particularly when different conditions are to be compared.

Some physical properties of water vapor

Specific gravity. For the purpose of this discussion, water vapor can be considered a gas subject to Avogadro's Law which states that equal volumes of different gases at the same pressure and temp contain the same number of molecules. From this, it follows that for a given volume of humidified air, each molecule of water vapor will displace a molecule of one of the components of dry air (for practical purposes, oxygen and nitrogen); from this, a number of logical conclusions follow. H_2O (atomic wt 18) is considerably lighter than either O_2 (atomic wt 32) or N_2 (atomic wt 28). Thus, as the water vapor content of a given volume of air goes up, its specific gravity decreases, making moist air lighter than dry. That the converse is usually firmly believed relates to the behavior of suspended particles of liquid water (as in fog), not to humidity as such.

Vapor pressure. The amount of water vapor that can exist in a given space is directly dependent upon temp. As Marvin (15) has pointed out, this quantity of water vapor is related only to the space involved and the temp. It is quite independent of the presence of air, exerting its own vapor pressure according to the principles of Dalton's Law which states that two or more gases occupying the same space at the same time behave independently of each other.

Specific heat. The specific heat of water vapor is ca. double that of air (0.4820 vs. 0.2404 at 100°F and 1 atm). Thus, the higher the moisture content of air, the higher its specific heat. From this, several effects follow that are of importance both in growing and in handling produce. Both sensible heat (that will register on a thermometer as temp) and latent heat (which originally converted the moisture to vapor rather than liquid or solid with no effect on temp) are affected. It takes more transfer of heat to change the temp of moist, than of dry air, whether the air is being heated or cooled. The effect is slight, however, the specific heat of air changing less than 1% when going from 0 to 100% at 10°C. Any addition of water vapor increases latent heat. If the moist air is cooled below the dew point (as discussed below) this latent heat will be released as the latent heat of condensation (ca. 590 cal/g of precipitated moisture, depending on the temp at which condensation takes place). If the temp is low enough for the water vapor to crystallize as ice, the latent heat of fusion will also be released (ca. 80 cal/g of moisture frozen). Thus, this increasing heat content of air with increasing humidity can be a serious factor in such instances as increasing the heat load on a refrigeration system when imperfect vapor barriers allow moist air to penetrate into the storage, an effect that is much more important in freezers than in coolers.

Total heat content (enthalpy) of the air approximates very closely to a value known as "sigma function" (Σ) on the psychrometric chart (Fig. 1). For purposes of this discussion they can be considered synonymous.

The relationship between humidity and enthalpy is strikingly illustrated in an example of atmospheres under freezing conditions (5). Air at 15°F (−9.4°C), 20°F (−6.7°C), and 25°F (−3.9°C) all have essentially the same total heat content of ca. 5.5 BTU/lb. dry air when the relative humidities are 100%, 40%, and 0% respectively, although at 15°F and 100% rh, 50% of the heat is present as latent, rather than sensible heat that shows as temp (Fig. 2).

This relationship between humidity and the latent heat content of the air is illustrated further in Fig. 3 showing 3 conditions, A, B and C, in which air is at 35°F (1.7°C) and 90, 50, and 10% rh, respectively. Differences in total heat content (13, 11 and 9 BTU/lb. dry air, respectively) are apparently minor. Nevertheless, the availability of this heat varies drastically under freeze conditions. For condition A, saturation (100% rh) occurs just before air temp drops to the freezing point. Moisture immediately precipitates, initially as dew, releasing its latent heat of vaporization. As the temp continues to drop, water vapor solidifies as hoar-frost with additional release of the latent heat of condensation. If only 114 lb. (51.8 kg) of water vapor is precipitated per acre as hoar-frost, 1,000,000 BTU/acre would be released on the surface of the crop (5). Under condition B, such release of latent heat would not occur until the temp dropped to 20° (−6.7°C), by which time most tender crops would be injured. Under condition C, no release of latent heat could take place even at sub-zero temp.

High relative humidity also mitigates the effects of freezes by: decreasing heat radiation to the sky; limiting evaporative cooling from moist or transpiring surfaces; and (when natural or artificial clouds are present) helping to maintain moisture droplet size above the 10 μ lower limit for effective back radiation of radiated heat. These effects and the relations between them are too complex for evaluation here.

Thus, it is humidity that makes the difference between a mild "white frost" and the dreaded "black frost" that kills because no latent heat is released upon the plant surfaces.

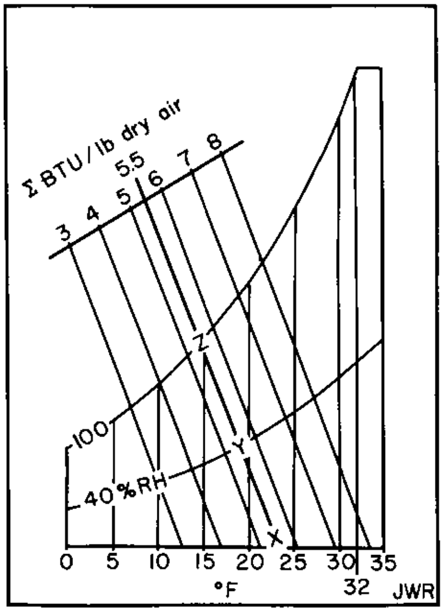

Fig. 2. Illustration of how air at 15°, 20°, and 25°F can have the same total heat content (Σ, BTU/lb. dry air or enthalpy) if the rh is 0% (X), 40% (Y), and 100% (Z), respectively. From (5).

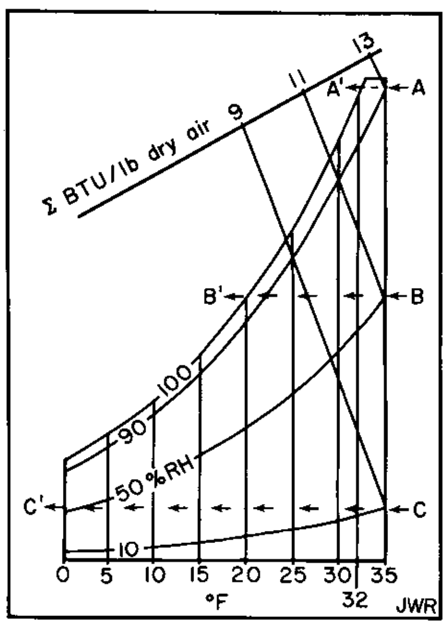

Fig. 3. Illustration of how frost hazard at prefreezing condition of 35°F (1.7°C) can vary with humidity. A (initial 90% rh) – Precipitation starts at A' before air temp declines to the freezing point, with immediate release of latent heat. B (initial 50% rh) – Precipitation (B') does not start until dry bulb temp is down to 20°F (−6.7°C) by which time most tender crops will have been destroyed. C (initial 10% rh) – Precipitation and subsequent release of latent heat will not take place even if temp drops to zero.

Interactions with other parameters

Many of the problems involving humidity in postharvest horticulture are related to sometimes unsuspected interactions between temp and humidity. Virtually any changes in temp will produce an associated change in relative humidity and sometimes the effect can be unexpected to the uninitiated.

Temp drop and dehydration. There is a tendency for periods of temp drop to be conducive to dehydration. Fig. 4 shows humidity changes within bags of oranges packed inside fiberboard cartons as they go through a simulated shipping and marketing experiment (6). Soon after packing, humidity within the bags reached 100% rh. On transfer to 40°F (4.4°C) transit conditions, humidity dropped drastically. The effect appears unlikely as air at 100% rh within a confined space might be expected to go through the dew point when the temp was lowered. However, the cartons are permeable and there is a severe diffusion gradient from the conditions within the bag at ca. 110 gr/lb. specific humidity and those in the refrigerated vehicle at ca. 30 gr/lb. This dehydration during temp pull-down persists even when the heat transfer from the air stream is taking place in a shower of cold water, as in an old-fashioned brine-spray cooler or a more modern "Humi-fresh" system.

Effect of fluctuating temp. It is a common observation that horticultural products begin to wilt more readily in a fluctuating temp than in a constant temp. The reason for this can be seen in Fig. 5, which shows a portion of the hygrothermograph record for a 60°F (16°C) storage room with direct-expansion cooling coils. The minor fluctuations in temp as the thermostat supplies or cuts off refrigerant cause surprisingly wide fluctuations in % rh. Each time the relative humidity drops, the absolute humidity drops also and the gradient out of the produce increases, with consequent increase in moisture loss. Fig. 5 also illustrates the effect of adding a mist-type humidifier. The same type of fluctuations in humidity take place, but at a higher level. Even if humidifier capacity is increased to provide 100% rh with the coil off, humidity will drop as the coil cuts in again. A better way to maintain a constant high humidity in such a storage room is to have a two-stage refrigeration system with circulation of chilled brine or glycol. With direct expansion refrigeration, the best way to maintain high humidity levels is to start with a sufficiently large coil surface, thereby minimizing the change in temp and consequent removal of moisture as the air crosses the cooling coil. The effect prevails at temp commonly used in

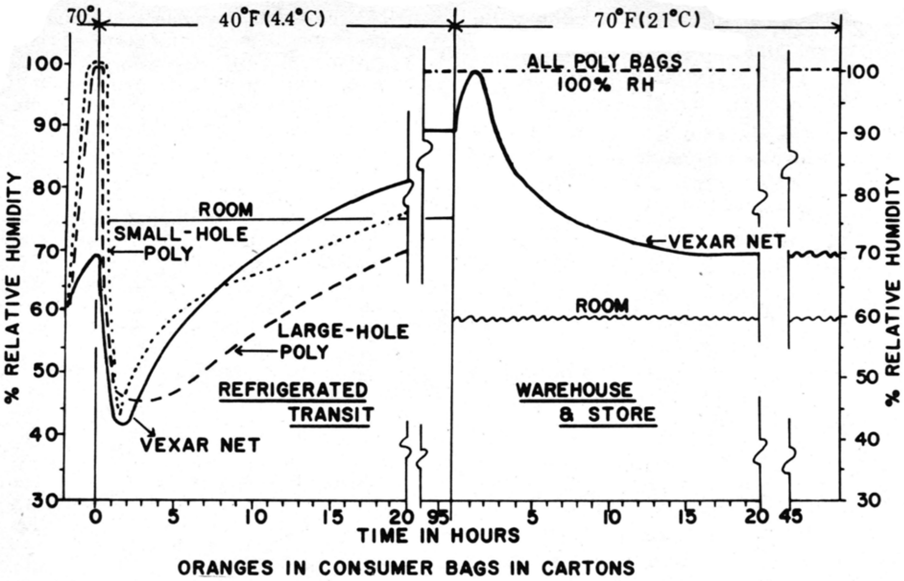

Fig. 4. Changes in % rh inside bags of organges in master cartons in a simulated transit experiment. This series involved: packing at 70°F (21°C); 4 days at 40°F (4.4°C), simulating refrigerated transit; 2 days at 70°F (21°C) and about 60% rh simulating warehouse and store conditions. This was repeated with 2 types of polyethylene film bags and one type of polyethylene net bag. From (6).

storage of horticultural products.

Air movement affects humidity in a closed system such as a cold storage or a growth chamber. The higher the volume of air circulated per minute, the higher the humidity. This is because the differential between the temp of return and delivery air ($\triangle$t) decreases as air volume being circulated increases, resulting in less precipitation of moisture on the coils. A failure to comprehend this relationship is usually due to confusion between air volume circulated (cu ft or m^3/min) and velocity (ft or m/min). In a closed system, raising the volume of air circulated per unit time will raise humidity, thereby decreasing transpiration and consequent shrinkage. Raising air velocity at a constant humidity (as when the wind rises in the open or when a fan is directed on stored produce independent of air movement across the coils) increases transpiration and hence desiccation.

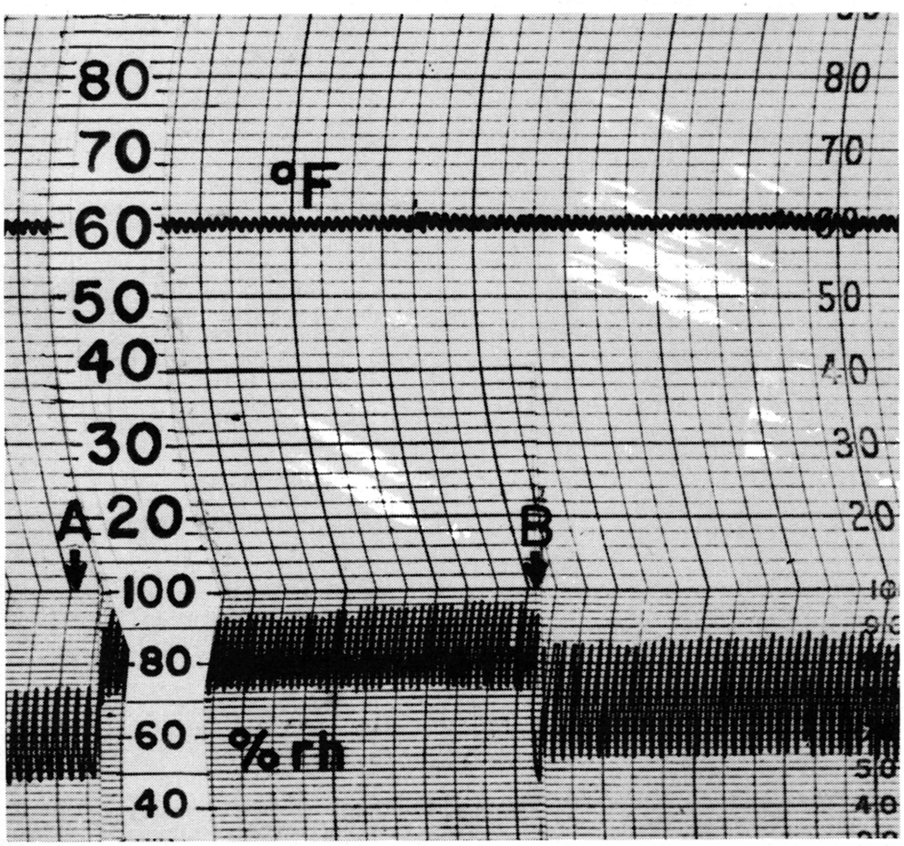

Fig. 5. Hygrothermograph record from a storage room cooled by a direct expansion coil and operating with and without a humidifier. Note: Temp is maintained at ± 1°F. With the humidifier off, % rh ranged from 50 to 70%, falling when the temp rose and vice versa. Between "A" and "B", a humidistat set at 96% rh operated a hydraulic-pneumatic mist humidifier. The humidifier could not overcome the downward fluctuations associated with the fluctuating coil temp.

Biological applications

Desiccation is the first obvious symptom of inadequate humidity levels. Desiccation results in a loss of quality for almost all fresh horticultural products (except possibly nuts). Drying can also be used as a form of preservation as in the preparation of dried fruits in which control of the humidity gradient from the product to the air stream can be of extreme importance. Unlikely as it may seem, maintaining a fairly narrow humidity gradient (as in a counter-current drying tunnel) can often result in better drying of such products. This is because too rapid initial drying can cause "case hardening" in which the outer tissues dry so rapidly that they form an impervious layer thereby impeding diffusion from the deeper tissues.

Desiccation of many fruits and vegetables is normally associated with wrinkling, but this only occurs when membranes remain intact. If the membranes lose their integrity, desiccation can take place without wrinkling. A classic example is freeze drying, in which freezing disrupts the membranes and, under the subsequent extreme vapor gradient, the product can desiccate without any change in dimension. This occurs when citrus fruits are frozen on the tree; often the peel (which is quite permeable) will remain alive, but the membranes around the juice vesicles are destroyed. Such fruit will desiccate almost completely while appearing healthy; the fruit that shrivel are those that are *not* severely frozen.

A curious, and economically serious, form of desiccation injury is stem end rind breakdown of oranges (16). This occurs when crops predisposed toward this malady are subjected to drying conditions between the tree and the washing and waxing operation. Such fruit appear normal when graded and packed, but a ring of peel tissue around the stem end collapses several days later and decay often sets in immediately. It is an unusual case in that the injury is due, not to holding conditions as might be expected, but to conditions prior to preparation for shipment or storage.

Wound healing is very much affected by both temp and humidity levels. Sweet potatoes will decay rapidly if placed immediately into storage at 12-15°C. However, after first being cured from 4–7 days at 30°C and ca. 90% rh, they can then be stored for 4–6 months. During the curing period, the wounds incurred in harvesting are healed but only if the humidity is high enough (13). Much more recent research (1, 8) has shown that under somewhat similar conditions, but even higher humidities, citrus fruits can also heal minor wounds. Healing of citrus involves lignin synthesis and occurs only at humidities well above 90% rh. Other products, such as apples and potatoes, can also carry out a certain amount of wound healing, usually by suberization at storage temp, but again only if humidities are high enough (21).

Very interesting examples of resistance to decay induced by very high humidities have been reported by van den Berg and Lentz (22). They found a decrease in decay for some types of root vegetables stored at extremely high humidity levels in jacketed storages. This is due to nonobligate parasites growing as saprophytes on the surface dirt and roots rather than penetrating the tissues.

Tissue permeability in apples has been reported to vary directly with humidity levels in storage (24). The same author reported the curious finding that in very high humidities, apples gained 3% in volume without corresponding gain in weight.

Chilling injury (CI), a very serious problem in storage and transport of fruit and vegetables of tropical origin, is sharply affected by humidity levels. The improved resistance to CI of "variety" bananas shipped in open ended plastic bags cannot be attributed to a controlled atmosphere (CA) effect but much more likely relates to the finding (18) that extremely high humidities greatly restrict the development of chilling injury. The same things has been shown for citrus fruits (19). On the other hand, *low* humidities have been reported to reduce low temp breakdown of 'Jonathan' apples (20).

Respiration. Perhaps the most far reaching effect of humidity on biological processes occurs through its effect upon respiration. Maximum respiration is typically attained only under conditions of high humidity, as Eaves reported as long ago as 1938 (3). More recent reports indicate that the effect is far more pronounced for bananas (7). A "chicken and the egg" situation exists with regard to whether other, more obscure, biological effects of humidity are caused by this effect upon respiration or whether respiration reflects the effect of humidity on other systems.

Biochemical effects of humidity on other systems are too numerous to report. Two examples might be of general interest. Kriedemann (9) has shown that photosynthetic activity of citrus leaves is related to humidity levels. Of immediate economic importance is the fact that inversion of sucrose in sugar cane is intimately associated with loss of moisture, and thus with humidity levels (10).

Those interested in a detailed dissertation on the biochemical properties of horticultural products as affected by humidity during cooling are referred to a paper by Fockens and Meffert (4).

Practical applications in produce storage

No attempt is made here to either deal with the physical and mathematical application of these principles to storage problems, nor to discuss the technology of such storage developments as the jacketed storage and the "Humi-Fresh" cooling unit. For those interested in such aspects, see (11). Readers interested in the mechanics of humidity measurement and control are referred to (17). For an exhaustive treatment see the 4-volume text by Wexler (23).

Conclusion

Probably as long as man has sought to store and transport horticultural products, he has realized that quality will be affected by humidity levels. In recent years, our understanding of the functions of humidity indicates that they are exceedingly complex. Hence, comprehension of the nature of humidity is necessary in order that it can be controlled properly. Moreover, there is an ever increasing demand for high quality produce at a time of decreasing efficiency and availability of hand labor and an increasing popular outcry against use of "preservatives." Skillful manipulation of humidity can never be legislated out of use, as may happen to any agricultural chemical.

Literature Cited

1. Brown, G. Eldon. 1973. Development of green mold in degreened oranges. *Phytopathology* 63:1104-1107.
2. Deason, D. L., and W. Grierson. 1972. Degreening at very high humidities: Humifresh-Filacell system vs. a pneumatic water spray system. *Proc. Fla. State Hort. Soc.* 85:258-262.
3. Eaves, C. A. 1938. Physiology of apples in artificial atmospheres. *Sci. Agr.* (Canada). 18:315-325.
4. Fockens, F. H., and H. F. Th. Meffert. 1972. Biochemical properties of horticultural products as related to moisture during cooling down. *J. Sci. Food Agr.* 23:285-298.
5. Grierson, W. 1964. Grove heating: Some thermodynamic considerations. *Proc. Fla. State Hort. Soc.* 77:87-93. (Reprinted in *Citrus & Veg. Mag.* 28(6):22, 24, 25.)
6. ———. 1968. Consumer packaging of citrus fruits. *Proc. 1st Int. Citrus Symp.* Vol. III:1389-1401. Riverside, California.
7. Haard, N. F., and H. O. Hultin. 1969. Abnormalities in ripening and mitochondrial succinoxidase resulting from storage of preclimacteric banana fruit at low relative humidity. *Phytochemistry* 8:2149-2152.
8. Ismail, M. A., and G. E. Brown. 1974. Phenolic content during healing of 'Valencia' orange peel under high humidity. *J. Amer. Soc. Hort. Sci.* 100:249-251.
9. Kriedemann, P. E. 1968. Some photosynthetic characteristics of citrus leaves. *Aust. J. Biol. Sci.* 21:895-905.
10. Lauritzen, J. I., and R. T. Balch. 1934. Storage of mill cane. *U.S. Dept. Agr. Tech. Bul.* 449.
11. Lentz, C. P., L. van den Berg, R. E. Hardenburg, D. Meredith, and E. G. Jorgensen. 1973. Relative humidity and the storage of fresh fruits and vegetables — recent research results and developments. *Symp., Amer. Soc. Heating, Refrig. & Air-Cond. Engrs.* 345 E. 47th St., New Yor, N.Y. (Five papers.)
12. Love, H. H. 1937. Application of statistical methods to agricultural research. The Commercial Press. Shanghai.
13. Lutz, J. M., and R. E. Hardenburg. 1968. The commercial storage of fruits, vegetables, and florist and nursery stocks. *U.S. Dept. Agr. Handb.* 66.
14. Mackey, C. O. 1947. Air conditioning principles. Intl. Textbook Co. Scranton, Pa.
15. Marvin, C. F. 1941. Psychrometric tables for obtaining the vapor pressure, relative humidity and temperature of the dew point from readings of wet and dry bulb thermometers. *U.S. Dept. Commerce, W.B.* 235.
16. McCornack, A. A., and W. Grierson. 1965. Practical measures for control of stem-end rind breakdown of oranges. *Fla. Agr. Ext. Ser. Cir.* 286.
17. Norton, Harry N. 1969. Humidity and moisture, Chapter 6 (p. 293-330) *In* Handbook of Transducers for Electronic Measurement Systems. Prentice Hall, Inc., Englewood Cliffs, NJ. (Reprinted in *Measurements and Data* 18:114-150, Nov.–Dec. 1969).
18. Pantastico, E. B., W. Grierson, and J. Soule. 1967. Chilling injury in tropical fruits: I. Bananas. *Proc. Trop. Region, Amer. Soc. Hort. Sci.* 11:82-91.
19. ———, J. Soule, and W. Grierson. 1968. Chilling injury in tropical and subtropical fruits: II. Limes and grapefruit. *Proc. Trop. Region, Amer. Soc. Hort. Sci.* 12:171-183.
20. Scott, K. J., and E. A. Roberts. 1968. The importance of weight loss in reducing breakdown of 'Jonathan' apples. *Aust. J. Expt. Agr. & Animal Husbandry.* 8:377-380.
21. Tetley, U. 1930. A study of the anatomical development of the apple and some observations on the pectic constituents of the cell walls. *J. Pom. & Hort. Sci.* 8:153-172.
22. van den Berg, L., and C. P. Lentz. 1973. High humidity storage of carrots, parsnips, rutabagas and cabbage. *J. Amer. Soc. Hort. Sci.* 98:129-132.
23. Wexler, A. 1965. Humidity and moisture, measurement and control in science and industry. Vol. IV. Reinhold Pub. Corp., New York.
24. Wilkinson, B. G. 1965. Some effects of storage under different conditions on the physical properties of apples. *J. Hort. Sci.* 40:58-65.

Calcium-related Disorders of Fruits and Vegetables[1]

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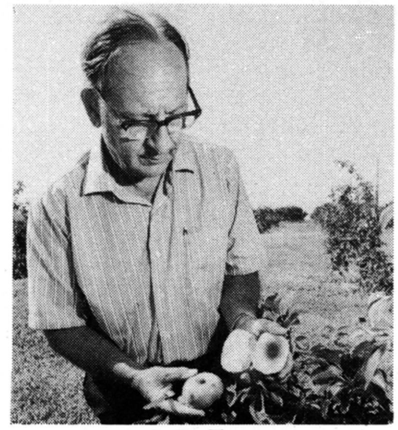

C. B. Shear

Calcium is the fifth most abundant element in the earth's crust, accounting for more than 3% of its composition. The exchangeable Ca content of a "normal" soil ranges from 65 to 85% of its total exchange capacity (12). Leaves of dicotyledonous plants generally contain from 0.5 to 5.5% Ca on a dry weight basis (44). The aboveground woody portions of trees in a 36-year-old apple orchard (35 trees per acre) contain about 200 lb. of Ca/acre as compared to about 175 lb. of all other nutrient elements combined (98). Recognizable foliar symptoms of Ca deficiency are seldom observed on field-grown fruit or vegetable crops. Despite these facts, serious economic losses occur annually from physiological disorders resulting from an inadequate level of Ca in the fruits, storage roots, or tubers of many plants or to the heart leaves of cabbage, lettuce, and other compact leafy vegetables.

Bitter pit (BP) of apples, blackheart of celery, and blossom-end rot (BER) of tomatoes have been recognized as physiological disorders since the middle of the 19th century, but only in 1936 for BP (14), 1944 for BER (74), and 1954 for blackheart of celery (26) was an inadequate level of Ca in affected parts implicated in any of these diseases.

The list of disorders now recognized as associated with a localized inadequacy of Ca includes BP (14, 17), cork spot (81), cracking (80), internal breakdown (5, 69), Jonathan spot (4), lenticel blotch (69, 75), lenticel breakdown (69), low temperature breakdown (101), senescent breakdown (54, 69), and watercore (69) of apples; end spot of avocados (35); hypocotyl necrosis of beans (79); internal browning of Brussels sprouts (56, 65); internal tipburn of cabbage (58) and of chinese cabbage (41); cavity spot and cracking of carrots (59); blackheart of celery (26); cracking of cherries (10, 92); blackheart and tipburn of chicory (97); brownheart (57) and tipburn of escarole (57); tipburn of lettuce (90); soft nose of mango (104); cavity spot of parsnips (33); poor filling of peanuts (7); cork spot of pears (102); blossom-end rot of peppers (36, 62); sprout failure (94) and tipburn (48) of potatoes; cracking of prunes (13); leaf tipburn of strawberry (53); black seed (20), blossom-end rot (21, 55, 64, 74), and cracking (15) of tomatoes; and blossom-end rot of watermelons (95).

Insufficient knowledge of factors affecting uptake and translocation of Ca by plants and of specific functions of Ca in metabolism have slowed progress towards understanding and controlling these and perhaps in recognizing other Ca-related disorders. Over the years, almost every environmental component and cultural practice has been shown to either aggravate or ameliorate these disorders. A chronology of the accumulation of these apparently unrelated bits of information and the eventual demonstration that each can be related in some way to Ca nutrition of affected tissue presents a unique example of interpretive synthesis in the unraveling of an intricate problem. As with any problem, the answer, once in hand, seems obvious.

I first will discuss those conditions that have been considered causes of, or agents in, the development of one or more of these Ca-related disorders. Then I will show how each condition is related to some aspect of Ca nutrition and assign each a logical position in the etiology of the disorders.

CONDITIONS INFLUENCING THE DISORDERS

Moisture

The first-described apple-spot disease now classified as a corking disorder was probably BP which, though probably recognized much earlier, was scientifically discussed as "Stippen" by Wortman in 1892 (103). He attributed the disease to abnormal transpiration. Later, McAlpine (60) thought the disease was produced by a shortage of water in the affected tissue as a result of either excessive transpiration or of too rapid growth. In 1918, Brooks and Fisher (9) reported cork spot (York spot), BP, Jonathan spot, and drought spot (probably B deficiency) all associated with irregular water supply. They concluded that late-season irrigation over-stimulated fruit growth, thus increasing susceptibility to pitting. Much work, both before and after that of Brooks and Fisher implicated excess moisture in the development of corking, though the evidence favored the drought theory (22, 31).

Low soil moisture was long considered the most important factor in the development of BER of tomatoes (89) though Stout (88) demonstrated that excessive watering also could promote its incidence. He concluded that over-watered plants were suffering from water stress induced by poor aeration. Similar conclusions were reached as to the effects of moisture fluctuations on blackheart of celery (11, 34), tipburn of lettuce (91), and internal browning in Brussels sprouts (56).

Other ambient conditions that affect the water relations within the plant have been shown to influence these disorders. Gerard and Hipp (30) showed that vapor-pressure deficits above 14-15 mm of Hg induced BER in 'Chico' tomatoes. McAlpine (61) considered excessive transpiration to be responsible for the greater prevalence of BP in arid Australia than in humid England. Geraldson (26) suggested that high temperatures, through their effects of increasing transpiration, might be partially responsible for the high incidence of blackheart in greenhouse-grown celery. Tibbitts and Rao (91) cited several investigations that have implicated high temperatures in the induction to tipburn of lettuce.

Light

Light intensity also has been related to the incidence and severity of these disorders. Wallace (93) reported higher incidence of BP in apples grown in exposed positions on the tree. Jackson et al. (42) showed that artificially imposed shade reduced the incidence of BP on 'Cox's Orange Pippin' apples. Tibbitts and Rao (91) increased the severity of lettuce tipburn with increased light intensities and/or extended light duration. Wedgeworth et al. (96) reported reduced BER of tomatoes with shading.

Solution concentration

Increasing the osmotic concn of the nutrient solution induced BER of tomatoes (76). Fruit on plants grown in solutions having an osmotic pressure of 0.08 atm was free of BER, but 80% of the fruit on plants grown at concn above 1.70 atm developed the disorder. Hori et al. (41) reported this effect of high salt concn on the incidence of blackheart of cabbage also.

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