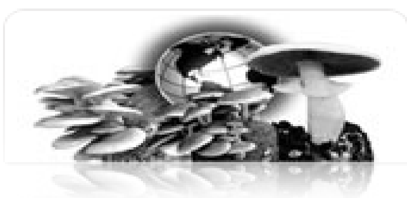

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Review

Ventilation for mushroom cultivation: the importance of the needs of mushrooms and of the gas laws

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ABSTRACT

Ventilation depends on physics, chemistry and especially the biological needs of the organism that is being provided for. The history of ventilation is about as long as the history of man. However, unlike many other things that make us more comfortable and the organisms we husband more productive, its application is often inadequately considered. Often we believe that others have already considered all factors and we need only to follow what they have done. Often we have copied more of their mistakes than of their careful thoughts. Also, most designers of ventilation systems are not sufficiently proficient in all three of the necessary sciences and associated technologies. This review is an attempt to look at all of the areas and discover ways in which design parameters for mushroom growing can be improved. Emphasis is not on how much air is moved, but on the way nature moves it and how nature can be aided to grow mushrooms with a minimum of air movement.

Key words: Gas densities, carbon dioxide, water vapor, HVAC, mushroom metabolism.

INTRODUCTION

For most reviews it is only necessary to cite publications on the subject and tell what they found from their research. Sometimes, several publications will disagree and then there may be need to give some discussion on why they disagree. However, heating and ventilation are subjects that have been studied for more than 250 years and have been practiced from prehistoric periods. Even primitive air conditioning has a long history. Ventilation in general, but especially for mushrooms, involves physics, chemistry and biology, but most modern physicists, chemists and biologists generally have little interest beyond personal comfort. While the laws of chemistry and physics do not change, various organisms have different needs and those needs do change the application and even the relative importance of some chemical and physical laws. Equally important are the effects of other conditions. Ventilation for other purposes may have much in common, but as we will see, they also have many contrasting differences. Things that make perfect sense for the environment of one organism may make no sense in ventilating for another. Mushrooms are neither plants nor animals and their ventilation needs are unlike those of plants, animals and humans. While one can find books on ventilation, there is very little on the needs of mushrooms. Because of the sparse research and the need to consider mushrooms more adequately, this may be more a pedantic review than a typical scientific review.

Although ventilation often seems simple, its many sides suggest that we must keep the requirements of mushrooms or other organisms in mind. At the same time it is useful to learn about the ventilation used for other organisms and to think why the ideas used may or may not be useful for mushrooms.

A review of publications on any subject, must, in essence, be a history of the subject. The first question the author of every review must answer is, how far back must I go? Or even better, what can we learn from things done years ago. Often, we learn that many questions were answered long ago and have been ignored by more recent researchers. I have decided to look for the oldest information I can find. However, when possible I looked for others who had already written about the very old material. Even while doing that, I have read and included writing of more than 250 years ago.

While one can wisely doubt the accuracy of things found only on the internet, it is difficult to find references to many topics by searching abstract journals and other more reliable sources. Many of those used are from institutions that are generally considered reliable and to have some particular expertize. In a few cases, the internet site is simply the source of a copy of an original document or of a transcription of such a document.

Ventilation is one of the most important parts of the physical environment, but living things generally want the ventilating air to be tempered. Temperature is the primary attribute that must be regulated. Ventilating and the process of tempering the air is now generally referred to as HVAC, the initial letters of the functions, Heating, Ventilation and Air Conditioning.

Penn State tells us that coal was first used for heating in the first century A.D., but did not become popular for many centuries, or about the end of the 17^{th} century[21]. Its slow rise to popularity is undoubtedly one of the most fortunate facts of history. In a very real way, coal is the antithesis of ventilation. Coal produces more carbon dioxide than other fuels with the exception of charcoal and more other poisons per unit of heat than any other fuel[5].

Air conditioning is much more recent. According to the Penn State web site, Willis Carrier built the first one in 1902[21]. However, they seem to be referring only to gas compressor units. In the May 16, 1903, *Scientific American* had an article on a device using ice and salt to cool air, it was designed by Willis L. Moore, Chief, U.S. Weather Bureau. The cooled air moved out of the bottom of the device.

While Carrier was very early to use a compressor to air condition, some doubt of who was first is left by a chronology at the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) web site[1]. Michael Faraday invented the gas-compressor refrigeration principal in 1824[10]. Again, the ASHRAE seems to disagree. Apparently the term, "air conditioning" and an invention for cooling air by water evaporation was the work of Stuart Cramer of South Carolina in 1906. Although they cite Cramer for coining the word, the ASHRAE chronology uses the term for many earlier installations[1,10]. The use of ice to cool air was rather the invention, in 1842, of John Gorrie, a Florida physician[2,13,25]. It has become common to consider cooling based on the evaporation of water as evaporative coolers, but in fact, almost all air conditioning depends on evaporation. In compressor systems, a "fixed" gas is compressed into a liquid, cooled to about ambient, then when it evaporates it cools its surroundings[26]. When it is again compressed, the heat energy it picked up while evaporating is concentrated and once again it is dissipated to the surroundings as it again becomes a liquid.

Benjamin Franklin was interested in keeping cool and invented a fan propelled by his foot or by rocking while sitting in his chair[11] (**Fig. 1**). He and Prof. John Hadley of Cambridge University experimented with evaporating diethyl ether until their thermometer read –14 C (+7 F)[27]. In a letter, written in 1758 Franklin recognized that evaporative cooling had long been used to keep water cool in "Indostan"[7].

Another type of air-conditioning has been used extensively, but in very limited places: Artesian aquifers – water from very deep in the ground, is often reliably very

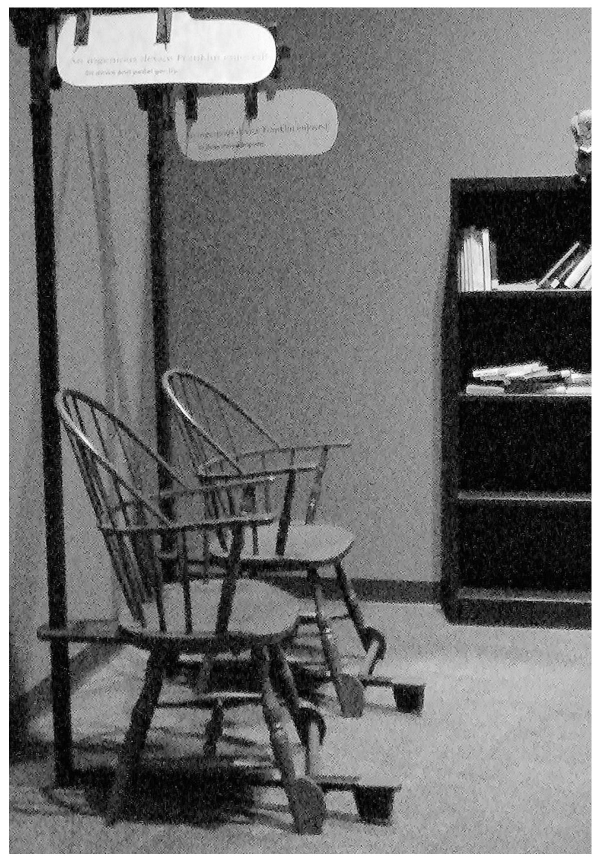

Fig. 1. Two working models of Benjamin Franklin's fan-chair. Just tap your foot and the board overhead fans you. These are part of a traveling exhibit of the Benjamin Franklin Tercentenary.

cold. Such water can be pumped through heat exchangers with air blown over the exchangers. There is such an aquifer under the city of Minneapolis. Apparently, one of the first to use it for air-conditioning was the State Theater in Minneapolis[19]. The theater was completed in 1921 and had a 255 meter deep well that provided cold water. Although not recognized by ASHRAE, it would appear to have been the first practical air conditioning in a public building. Soon large stores and some office buildings drilled their own wells. The practice continued into the 1950s, but early in the 1960s it was recognized that the practice was depleting a valuable resource and the practice was ended.

Although the second letter of HVAC, "V", stands for "ventilation," when one looks up HVAC history on the internet, one finds information on heating and air conditioning, but hardly a mention of ventilation. When ventilation history is searched, machines for maintaining human breathing are at the top of the list; few entries deal with building ventilation and they are scattered towards the end of the list.

Travelers often learn of ancient technology: "Haeinsa on Mt. Gayasan, where a collection of more than 80,000 woodblocks engraved with Buddhist scriptures is kept in a naturally cooled and controlled environment. The building, built in 1488, was designed with an adjustable ventilation system to prevent deterioration of the books"[4].

One simple way to cool is to use very heavy construction with very high ceilings and a good opening at the top and another at the bottom. The moist hot air will gather at the top and as it leaves, pull in cooler air at the bottom. Such structures made with mud and thatch are used by natives in Africa, but the design was exaggerated in the construction of the cabanas in Gorongosa National Park in tropical Mozambique (**Fig. 2**). As the outdoor temperature cools in the evening, the air in the upper area is much warmer than the surrounding air, so it moves out and the evening air moves in quickly. Although the cabanas are also equipped with mechanical air-conditioning, it is generally unneeded.

OTHER INDUSTRIES WITH USEFUL HISTORIES

Apparently the earliest indication of man making provisions for ventilation were in mines. Mining has a long history of need for ventilation, so it is reasonable to look there. Even more so, because mushrooms have been cultivated in mines, caves and other underground places. We are told that, "between 4000 and 1200 BC, European miners... built brushwood fires at the working faces... However, those Neolithic miners could hardly have failed to observe

Fig. 2. A cabana at Gorangoza National Park, Mozambique. Walls are thick concrete the roof is true thatch and is also the ceiling. Note that the peak is built to allow the hot moist air to escape.

the currents of air induced by the fire". As early as 600 BC, Greek silver mines had at least two airways, serving each major area. There is evidence that one airway carried fresh air from the surface and the other the exhaust air. Pliny (23-79 AD) told that slaves used palm fronds to move the air[18].

The history of mining ventilation is "full of lost discoveries and rediscoveries, excitement and despair, achievement and tragedy"[18]. The history of ventilation in mushroom houses may be too short to say the same. Yet, if we look at mushroom house ventilation as dependent on the lessons learned in mines, the same statement seems to apply. McPherson names dust, gas emissions, heat, humidity, fire, explosions and radiation as the hazards that ventilation must address[18]. The last three have generally not been a consideration in ventilation for mushroom cultivation. However, fire has occurred, especially in composting, radon can be a problem that ventilation can handle in almost any location below grade, even a home cellar. We would not expect explosive gas in mushroom growing, but it can happen if mines or caves are used for cultivation. Dust is another fuel for explosions. It may be difficult to think of spores as dust, but most domestic and outside dust includes spores. It may also be difficult to think of anything of a biological nature as being an explosive, but the dust in flour mills has often exploded. Until late in the 19th century flour mills were normally small, but in 1874, C. C. Washburn built his original "A" mill with a capacity of 3000 barrels of flour per day, four years later, it exploded killing 18 workers and scattering debris over several square miles[6,20,23]. Fortunately, it happened at 7:20 PM after most workers had gone home. The mill was totally leveled, two neighboring mills were completely destroyed, three more gutted by fire and a number of other buildings were damaged. A new mill was built to replace it. Washburn's company eventually became General Mills and they operated the new "A" mill until 1965. The mill suffered a number of calamities, but today it is an unusual museum called the Mill City Museum. Some of the original ventilation equipment, including cyclone separators used to collect flour dust have been preserved, but are not used (**Fig. 3**). Modern ventilation has reduced the number and severity of flour dust explosions, but they still occur occasionally. The reduction in those problems was in large part the result of a rare occurrence for 1874 and even for today; the coroners court used scientific experiments to determine that the cause was dust and the U.S. Department of Agriculture soon propagated the information to other millers[6,20]. Small flour explosions have been used to teach the danger to flour mill workers and also to entertain museum patrons (**Fig. 4**).

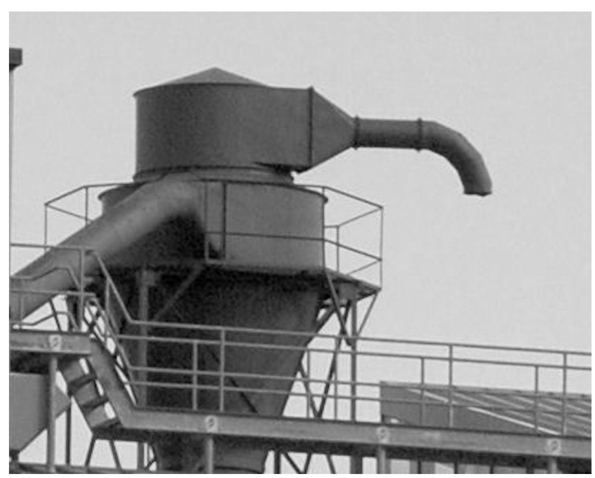

Fig. 3. A cyclone separator atop Washburn/ General Mills, Mill A/Mill City Museum. The unit removed dust from the mill ventilating system. An important protection from explosions.

Fig. 4. A flour dust explosion demonstration. The top of the building had been tightly covered with two layers of newspaper. The actual explosion blew the paper away and the flames seen here follow immediately, but last only a fraction of a second. The building is about 40 cm tall.

The author is not aware of any explosions in mushroom houses, but there are verbal reports of spores filling growing rooms like a heavy fog. Such conditions represent poor management, a waste of food, endangering workers' health, and probably a predisposition to explosions. The numerous fires in composting areas, have been attributed to self-heating, resulting in spontaneous combustion. They may now be less common, because forced ventilation is used in tunnel composting. Yet we might expect an increase in the fires in growing buildings. It is now common to grow mushrooms in compressed blocks of compost (**Fig. 5**). The Dutch and Italians have promoted similar lightly composted or un-composted blocks for *Pleurotus.* Such blocks will self-heat and especially if the ventilation system fails, they may someday spontaneously ignite. In addition to regulating gases, ventilation is very important in regulating temperatures.

Medical history may also shed some light on the broad subject of ventilation: "The hospitals of the later Middle Ages were grand affairs which were specifically built to be hospitals. The Hotel-Dieu in Paris had regular nurses (nuns), only 2 people per bed, good ventilation (for the time), and good waste disposal. This was the epitome of the medieval hospital indeed!"[17].

When the black-death struck in 1354, ventilation seemed to have played a part: "We can take heart in some of the human caring that was present. The nuns at Hotel-Dieu stayed with the sick until the staff was completely changed several times. The doctors thought a person's gaze or the stench of the disease could transmit it, and so covered themselves with thick clothing and held cloth to their noses. Some wore elaborate masks shaped like birds' heads which had holders for burning incense in the beaks"[18].

We do not know when the Italians first called the deadly disease, "mal'aria," thinking it was from poisonous vapors, but in 1740 Horace Walpole introduced the word to English and was shortened to malaria early in the 20th century[12]. Today we know it is transmitted by mosquitoes. While it is not the air, as such, the mos-

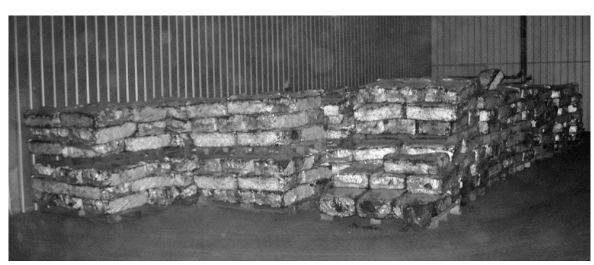

Fig. 5. Spawned, *Agaricus* compost blocks ready to be moved to growing shelves.

quitoes need the air to fly from and to their victims. Maybe with tongue-in-cheek, we should call mycophageous flies, "mushroom malaria". Screens and nets are good control methods for both mosquitoes carrying malaria and flies that eat mushrooms.

Recently, Google has "reprinted" Reid, Ventilation in American Dwellings (1858) on-line and BiblioLife has published a paper copy[22]. Considering that it is 150 years old, it expresses a great depth of understanding and practical suggestions. Practical mechanical ventilating equipment was not yet available, so Reid describes ways to use fire to ventilate. He is very concerned with the foul air causing malaria and the like. Science has allowed us to find a little humor in the belief that foul smelling air causes diseases, but it should not lessen our respect for the outstanding contributions to ventilation.

Reid did acquire considerable acclaim in his own time, he was commissioned to design new ventilation for the British Parliament. In support of his commission, a Dr. Birkbeck spoke to a committee of the British Parliament in 1835 and stated, "I have never seen a room ventilated, with strict reference to the whole purpose of ventilation ..." Then more particularly of the Houses of Parliament: "The smothering system adopted at present is terrible; I am sure, I for one, would not endure it for the service of the public"[9]. While mushrooms have no feelings, their physiology does react to atmospheric conditions and they may not endure the atmosphere in some mushroom houses.

"There is another point that requires much attention, and without which no adjustment for ventilation can be expected to give any satisfaction, and that is a reasonable view of all the ventilation may and may not be expected to accomplish"[22]. D. B. Reid, M.D., wrote those words in 1858 in his classic book, Ventilation in American Dwellings. That statement and many others are as true today as they were in 1858. The book is worth reading if only to appreciate how far medicine has come since that day and how little ventilation practices have improved. In 1858, they had need for ventilation that is now of little importance. Artificial lighting was always supplied by fire, *e.g.*, gas lamps, candles, etc., so ordinary rooms always needed ventilation to remove carbon dioxide, carbon monoxide and other gases produced in combustion. The removal of carbon dioxide from areas where there is considerable respiration is just as important now as it was then. However, if it will be formed near room temperature, its immediate physical behavior will be quite different from hot carbon dioxide formed by fire.

Ventilation needed by farm animals differs somewhat from provisions needed for humans and quite greatly from the needs of mushrooms. Harms[8] has written a book detailing the ventilation needed in buildings for housing farm animals. Farm animals are often kept in open shelters when outdoor temperatures are warm. However, in cold weather it is more common to keep them in closed, unheated buildings. Their own body heat is held in the building, so they are more comfortable. However, without some provision for ventilation the moisture from their respiration and evaporation from the surfaces of their bodies, urine and manure can easily be a problem. The problems and the solutions are discussed and finally reduced to mathematical formulas. The book is well written with generally clear descriptions. It seems a good source of information to be used for mushroom growers, but only by those with a clear understanding of the differences between animals and mushrooms and only with a clear understanding of the needs of mushrooms. Although it contains much useful information, both growing conditions and the needs of mushrooms are very different. Animals produce considerable heat, so the carbon dioxide that they produce is warmer than the general temperature of the building. As a result, the warm carbon dioxide is close to the density of the ambient air. Furthermore, animals forcefully expel their respiratory carbon dioxide, causing turbulence, which immediately mixes it into ambient air. Their heat and action is unlike the passive emission of carbon dioxide by mushrooms. The combination of breathing, body heat, the movement of bodies, tails and wings all provide for mixing of the gasses. No similar mixing occurs in mushroom houses. As we will see, there are also other important differences. While growing mushrooms do produce some metabolic heat, it is generally, although not necessarily, negligible compared to the heat produced by farm animals.

Apparently Harms misunderstands farm animal metabolism and treats carbon dioxide as of little importance in ventilating animals. It is true that hydrogen sulfide, ammonia and some other gasses from feces and urine are very unpleasant and can even be poisonous. Also, condensing water can be uncomfortable and cause the building to rot. However, if those were the only needs, as he suggests, a good system to remove solid and liquid wastes and controlled condensation with the water forming on a bare metal section of roof that drained away from the animals would be wiser than forced ventilation during cold weather. Mechanically powered methods for removing animal wastes in dairy barns have existed for about 70 years and Harms describes a method for pigs. Those wastes must be removed, and sooner is better. In his defense, if one uses sufficient ventilation to take care of the problems of waste and moisture, carbon dioxide will be taken care of.

Carbon dioxide is of the greatest importance in ventilating mushroom houses. While high humidity is needed for mushrooms, it is very undesirable for animals. In order to maintain a constant high humidity, the temperature must be closely controlled for mushrooms, but animals have a relatively wide comfort range. With the many differences, knowledge of good ventilation for animals is still of value for mushrooms, but only for the general principals and equipment for moving and to a lesser degree, controlling air temperature. That would include, fans, ducts ("polytubes"), controls, heating and cooling. Unfortunately, while he does suggest that his information is being out-dated by modern electronics, Harms treatment of controls is at best confusing.

Civil and agricultural engineers like to talk about slug-flow and ventilation by dilution or mixing. However, physicists generally speak of streamline or laminar flow and turbulent flow. Slug-flow is the concept that a fluid (liquid or gas) can be moved as a coherent mass, through a pipe or from one side of a room to the other. It assumes that conditions are such that there is no turbulence and it neglects friction. On the other hand, streamline or laminar flow assumes that there will be friction at the walls or other parallel stationary objects and that the fluid closest to the wall will move more slowly and that furthest from the stationary objects will move at the fastest speed. It also assumes that fluid at any given spot will continue to move at the same speed as long as the force on the fluid and the resistance to flow remains constant.

Turbulent, dilution and mixing are really just different aspects of the same concept. It is reasonable to expect a fluid to pass down a smooth pipe as laminar flow and laminar flow may approach slug flow in large pipes or other smooth conduits with little friction or other resistance. If we could send an even flow of air through a simple, empty room, we might also get laminar flow however, the reason we want to move the air through our room is to ventilate the organisms occupying the room. No matter what organisms, they, their food or substrate, objects used to hold them in place and possibly structural supports for the building, will cause turbulence, so laminar flow is not possible. Even the breath of animals will cause turbulence. However, mushrooms do not move about and they do not breath forcefully. The result is that little turbulence is caused by mushrooms compared to animals.

Mushroom houses have stationary objects that cause turbulence. Since moving objects, including various maintenance and picking activities, will occupy a small percentage of the total growing-ventilation time, turbulent mixing will be primarily in the immediate area of objects and particularly where they terminate, for example, the edges of shelves and around bags. The result of all of this is that while air turbulence occurs in mushroom houses, the turbulence is not generally adequate to mix the air well enough to result in air that is the same in all parts of the room. The gas laws, the locations of substrate, air ingress and air egress all have a strong influence on the composition of the air. However, a few houses may have recirculating fans that make the air nearly homogeneous.

Assemblies of humans can cause environments to be similar to those with farm animals, however, in most cases there will be supplemental heating or cooling, in addition to body heat. The additional heat will generally keep the temperature above the dew point, so less condensation will occur. Yet it is not unusual for condensation to occur on windows, cold walls and ceilings. The problems of condensation in animal barns are well handled by Harms and most apply, at least in part, to mushroom houses and buildings occupied by humans as well as those occupied by farm animals. However, unlike buildings for humans and animals, high relative humidity is required for mushrooms. Condensation in mushroom houses, in addition to damaging the building, may occur directly on, or drip on mushrooms and result in damage. Generally it will result in a decrease in relative humidity and except for condensate that lands on the mushrooms, it may cause drying of mushrooms. Both condensed liquid water on the mushrooms and drying can be detrimental to the mushrooms. That means we must have greater control over humidity and therefore, over temperature in mushroom houses.

Nature must provide ventilation for naturally occurring organisms. We are all familiar with breathing by mammals, and most mammals need ventilation for controlling temperature, humidity and other aspects of comfort in addition to breathing. Furthermore, many organisms do not have the ability to move air. Mushrooms have considerable need for ventilation; yet the ventilation provided by nature is not immediately obvious to the casual observer.

MUSHROOMS AND THE FACTORS OF IMPORTANCE TO THEM

The information above is about general ventilation, heating and cooling methods.

Although there are hints that mushrooms have different needs and that methods used by others may not be appropriate for mushrooms, no specific information is given. In order to be of value, specific information is required.

The careful observation of nature can tell us many things about the needs of mushrooms, as well as the needs of other wild organisms. Such observations have been made and reported. Like most living things all mushroom mycelia requires three things: water, oxygen and substrate (food). For parasitic and mycorrhizal species, the substrate may be a living host. It may also be a dead tree or other large piece of wood for many species. However, for many other species the substrate will be leaves, animal manure or other debris. Rain will carry such debris to a depression or other low point, normally the debris will remain and the water will seep into the earth or evaporate, but the depression will remain moist for longer than its surroundings. It would seem then, that the logical place to find mushrooms would be in depressions. Yet, mushrooms that do well on small debris, parasitic and mycorrhizal species are more generally found on slopes, including hillsides and even road cuts. Such locations are not very conducive to substrate accumulation and will not accumulate water, but they may be a place where seeping water surfaces.

The location of wild mushrooms is of importance to both mycologist and amateur mushroom hunters. Knowledge of natural habitats can usually be used by mushroom growers and mushroom cultivation scientists to optimize their growing conditions. So, we can ask, what does their location in nature tell us about their need for ventilation? Certainly the quantity of oxygen varies little from depression to slope and as mentioned water and substrate would seem to be less.

Kurtzman[14] has described a number of observations. He noticed that mushrooms seem to defy their natural needs. **Fig. 6** shows mushrooms growing on slopes. **Fig. 7** shows mushrooms growing above the ground on wood substrates. **Fig. 8** shows them in depressions in a windy area. All of those conditions have some problems in collecting and keeping water. Slopes have difficulty holding much substrate. All places shown in the figures, would have plenty of oxygen. However, while water, oxygen and substrate are required, most mushrooms also must have an atmosphere that is low in carbon dioxide. Like water and particulate debris, carbon dioxide also accumulates in depressions. The gas laws tell us that carbon dioxide is denser than other common atmospheric gases. In part it states that one formula weight of gas occupies 22.4 liters at standard temperature and pressure. The formula weight of nitrogen is 28, of oxygen, 32, while carbon dioxide is 44. Thus, carbon dioxide is 57% more dense than nitrogen and 37.5% more dense than oxygen. While the gas laws are based on standard temperature and pressure, mushroom houses will rarely have those conditions. At other temperatures and pressures those densities are inaccurate, but since both the temperature and pressure of all the gasses will be nearly homogeneous in a given house at a given time the relative densities will be as the gas laws predict. Another property of gases is that they dissolve one another. However, sugar dissolves in water (coffee, tea, etc.), but when sugar is put into water it settles to the bottom; if it is not stirred, some will dissolve, but even most of the dissolved sugar (syrup) remains in the bottom. When we drink to the bottom of our unstirred cof-

Fig. 6. Mushrooms on slopes. The slope allows the carbon dioxide to flow away[14].

fee cup the sugar and maybe syrup is still there. The same is true of CO_2 added to air; it also settles to the bottom.

Another observation is that when the air is dry, mushrooms dry out more quickly than most other terrestrial organisms. Microscopic examination tells us that unlike those organisms that dry more slowly, mushrooms have neither skin nor cuticle. Excluding the basidia and spores, the surface cells are essentially the same as the internal cells. If we did not know that mushrooms dried easily, the microscopic examination would suggest that the surface cells have the same needs as the internal cells. The internal cells are surrounded by other cells containing considerable water. The only thing we can do to provide moisture to the surface cells is to provide high humidity in the air. A formal description of high humidity is high water vapor pressure.

Water is a strange substance. In general its behavior is different from that predicted by its chemical formula, H_2O. However, water vapor does behave essentially as predicted. That is, the formula weight of water is 18, so water vapor has the lowest density of any of the common gasses in

Fig. 7. Mushrooms on wood in nature, the wood holds the mushrooms above the ground and allows carbon dioxide to flow away[14].

air. Nitrogen is 56% more dense than water vapor and carbon dioxide is 144% more dense than water vapor. Thus, water vapor will tend to concentrate near the ceiling of our mushroom house. That fact seems contrary to our observation. But we must remember that while we see water and ice, we do not see water vapor. We perceive that the air in places near the earth and especially those below the earth are generally more humid than those well above ground. However, places near or below the earth are generally cooler and cool air is able to hold less water vapor than warm air. Our perception depends more on the ability of the air to hold the moisture (the relative humidity) than on the total amount of water vapor in the air (absolute humidity). In addition, evaporation is more likely to be occurring from the earth, and the water vapor becomes diluted as it rises in dryer air.

So we want to remove the carbon dioxide and keep the water vapor. That is at once more difficult and easier than many understand. Unless considerable effort is made to stir the air, in order to remove the

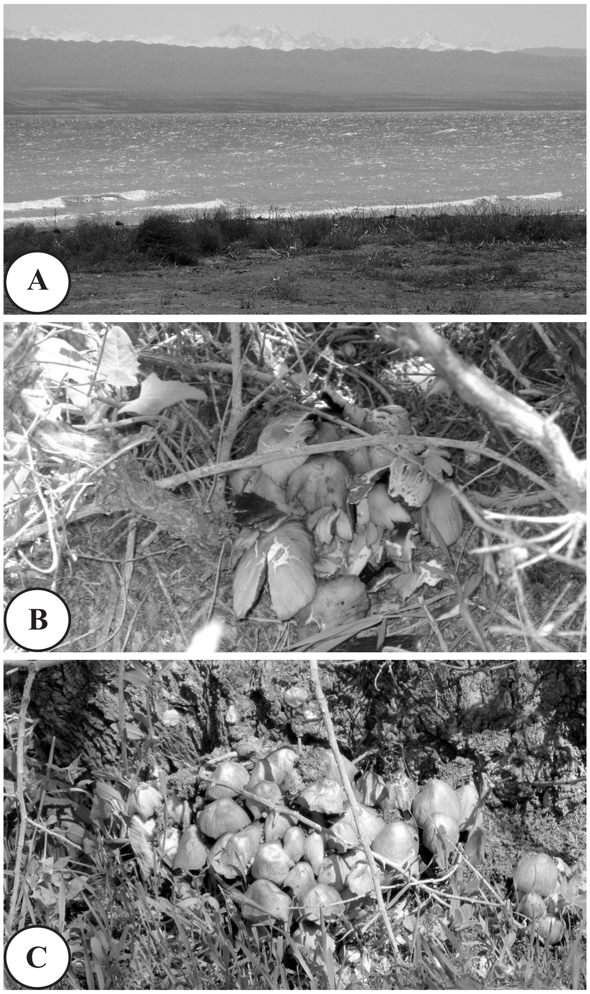

Fig. 8. A: The Kayrakkum reservoir, east of Khujand, Tajikistan. B-C: *Coprinus* growing in a ditch on the north edge of the reservoir. The moist wind from the reservoir blows carbon dioxide away, and provides the needed humidity. *Pleurotus* was also found, but was desiccated[14].

dense (heavy) carbon dioxide, the air must leave the room below the lowest growing area. With a ventilation system that uses fans only to blow air into the room, the exit plenum must be near the floor. The importance of the location of the air exit can be seen in rooms where the air is removed far above the floor with a resulting loss in mushroom yield on the lower shelves (**Fig. 9**). If gravity is the only force available, there must be an exit at floor level. In order to keep moisture in the room, it is wise to keep the floor wet at all times. Unfortunately, that means that the primary source of water will be very near where the air is leaving the room. With gravity ventilation, the loss of water vapor will be relatively small because the air will not move fast. However, with fans, the air with water vapor from the floor will leave more quickly, but water vapor can be added to incoming air and it will be easier to control the temperature. Controlled temperature is the most important factor in controlling the water vapor in the air.

Yet there is a great danger in over generalizing. Condensation of water is bad in almost any building and for all mushrooms, but the optimal humidity varies some with species. Once again, nature gives us good hints. Members of the genus *Agaricus* in the wild are generally found in open places. They must be able to stand some direct sun and dry winds. Most other cultivated mushroom genera, *e.g.*, *Pleurotus* and *Lentinula*, in nature, are generally found in forests. The forest provides considerable protection from both wind and sun, so we can expect them to have a greater need for high humidity. Also, *Agaricus* is generally cultivated on a horizontal bed of compost with casing, while most other mushrooms are cultivated on vertical surfaces of fresh substrate, often through holes cut in plastic. Barber has pointed out that the microenvironment is very important and complex in *Agaricus* cultivation[3]. He discusses the gradients of water vapor, CO_2 and heat. In general, limited heat is created by the mushrooms, but that heat added to the heat from the compost raises the overall temperature which increases the metabolism

Fig. 9. Looking down on *Agaricus* pins in a room with the ventilating exit air duct about half-way between the floor and ceiling. Notice more pins are visible on the upper shelves and the number decrease in lower shelves.

of all organisms in the area, which increases the heat, which in turn increases the metabolism so it can "spiral" out of control until the heat damages the organisms, and at worst, causes a fire.

When the moist substrate is hotter than the mushrooms, the warm water vapor from the hot substrate condenses on the mushrooms and puts them at high risk to blotch caused by *Pseudomonas tolaasii*. The solution is to increase the velocity of air and to reduce the humidity. Any change in air temperature can compound the problem. Cooling the air will cool the mushrooms faster than the substrate, thus encouraging condensation. Increasing the temperature will result is greater evaporation. With *Agaricus*, moderately dry air reduces yield, but increases quality. The problems of heating and condensation on the mushrooms is less with mushrooms growing on fresh substrate, but self-heating can cause the mycelium in the substrate to be killed. Water vapor from the substrate is greatly reduced in mushrooms grown from plastic bags. In general, the mushrooms are growing from holes that are small compared to the mushrooms. In addition warm water vapor is more likely to move upward away from the mushrooms and dilute in cooler ambient air, before it passes any mushrooms. The carbon dioxide, unless well heated, will tend to fall off a bag and also be less of a problem. It should be emphasized that like most mushroom diseases, *Pseudomonas* blotch is spread by poor sanitation; moisture is necessary, but only a contributing factor.

Specific specifications for directing air from a poly tube plenum have been described[15]. It was claimed that the air must be shot from a central plenum through jets towards the wall at such a velocity that it reaches the wall, but does not bounce off of it. It was also indicated that no air should leave from the bottom of the plenum. No other configuration is discussed except a few words about using small holes with flaps attached rather than jets. The primary reason given for no openings on the bottom of the plenum is that it will keep warm air from rising. Yet there is no reason given for wishing that the warm air will rise and no indication of how stale air should leave the room. Although nothing is said in the text, arrows in a drawing show that with the air forced to the walls from the plenum, it will tend to return across the beds and any air added from the bottom of the plenum would tend to counter that flow across the beds. Since he wanted the warm air to go up and he describes no exit for the air, we must assume that he plans to remove the stale air in the center of the ceiling. That suggests that the CO_2 will gather in the lower part of the room.

A prime purpose of ventilation, for most living things, is the removal of CO_2 so it seems quite sensible to use measurements of CO_2 to control ventilation. Apparently, that was first done in 1974[24]. Sampling ports were placed on the bottom of trays and one infrared spectrophotometer used for many sampling ports. Pneumatically operated servo dampers were used to control air flow. The placement of the sampling ports suggests that they wanted to only know the minimum CO_2 concentration in the immediate growing area. In modern time with greater emphasis on conservation of energy, a multi-speed fan or several independently controlled fans, as suggested by Harms[8], would seem more appropriate than the dampers.

An interesting experiment arranged mushroom growing trays in a manner that amounted to growing mushrooms in ventilation plenums[16]. There were six "plenums," each five trays long. The production of each tray was measured separately, but there was no significant difference. Single point measurements showed that the CO_2 declined and the bed temperature increased shortly before harvest. It appeared that the mushroom caps were so crowded that they held the CO_2 and heat in the substrate. It seems reasonable, although we could wish for more data, to conclude that bed temperature and not CO_2 is the most useful guide to ventilation requirements. It might also suggest that higher mushroom yield per unit of surface area is not the wisest goal. If good ventilation is not possible, quality and the total yield per unit of substrate may be compromised.

While dictionary definitions of ventilation vary, it is common to think of it as those early miners. Reid[22] and Harms[8] thought ventilation is a process done to remove stale or dangerous air. Yet, the author has been unable to find a single paper on ventilation, for mushroom cultivation, which discusses the mean of removal or route of stale air from mushroom houses. Most buildings leak air, so that if air is simply added, the excess will escape, somehow. The designs discussed by Reid are the only designs found that consider both the way air will enter and leave the room (**Fig. 10**). In all cases when we ventilate a building, we assume the air in the building is not fresh and the point where fresh air enters has a different composition than much of the air in the building. The fresh air entering is every bit as likely to leak out as is the stale air, albeit there may be more stale air and therefore more adjacent surface for it to leak. There is no point in blowing fresh air into the

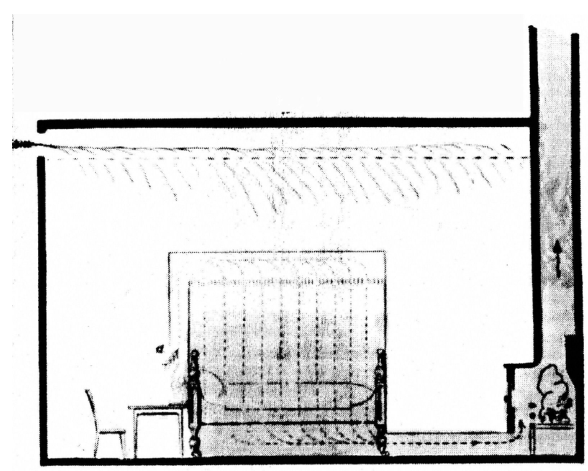

Fig. 10. A drawing from Reid, Ventilation in American dwellings. Note that he prescribed both the air ingress and the egress.

building, if the air exiting the building has the same composition. Rather we want the exiting air to have a composition very similar to the most stale air in the room or better contain more of the "staling" ingredients. Thus it would seem that any useful experiments on ventilation for mushrooms must discuss the exit of the stale air.

It is interesting that while the author has found no discussion of how air leaves mushroom growing rooms, most if not all articles discussing tunnel composting show air being blown in from under the compost and exiting near the ceiling. It should be noted that all phases of composting are very different from mushroom growing and this review is not intended to consider composting.

In conclusion, there is a need for much greater focus on what Reid told us 150 years ago: "that is a reasonable view of all the ventilation may and may not be expected to accomplish". That need is especially great in mushroom growing facilities.

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