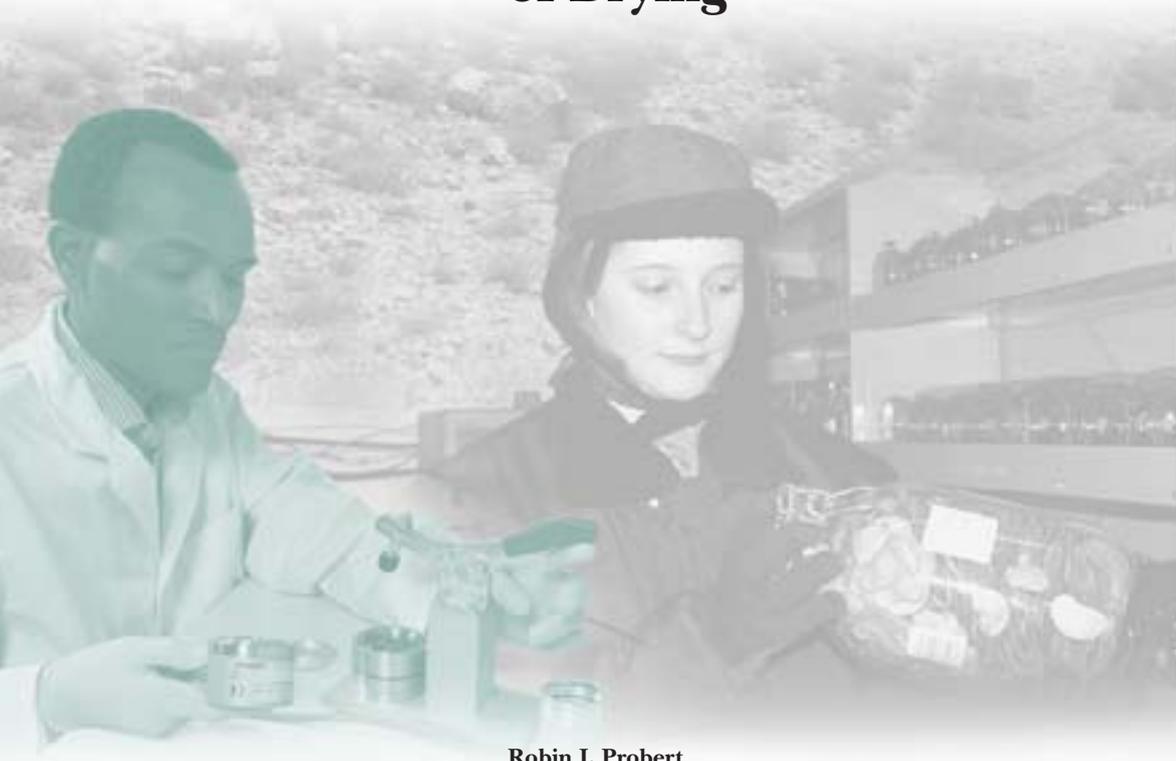


Chapter **19**

Seed Viability under Ambient Conditions, and the Importance of Drying



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Summary

The moisture status of seeds at the time of harvest is usually high and not in equilibrium with prevailing ambient relative humidity. Depending on temperature, the rate of seed deterioration (loss in viability) under field conditions may be unacceptable. Rather than rely on meteorological records to predict the behaviour of seeds in the field, instruments are now available that enable real-time measurements of seed moisture status. Practical advice for post-harvest seed handling based on such measurements is provided. The principles of seed drying are outlined and data is presented for the first time, demonstrating the potential of charcoal as a low cost, low technology seed desiccant.

Introduction

Grains of shatter-resistant cereal crops, though severed from the maternal vascular system, typically remain attached to the panicle long after peak maturity. As a consequence, seed moisture content (MC) at harvest will be relatively low and in equilibrium with ambient relative humidity (RH). By contrast, wild plants typically disperse their seeds at much higher moisture levels (Hay and Smith, 2003 – Chapter 6). Also, the variety of inflorescence structures exhibited by plants and the consequent variation in flowering and seed ripening times, means that seed collectors are often confronted with considerable seed developmental variation. Conventional wisdom advocates that seed moisture content must be reduced to a low level as soon as possible after harvest to maximise potential seed longevity in subsequent storage. More recently however, the potential benefit of delayed or slow drying treatments for seed collections containing immature seeds and fruits has been elucidated (for recent reviews see Probert and Hay 2000 and Hay and Smith 2003 – Chapter 6).

This chapter sets out to illustrate the effect of ambient conditions on the viability of orthodox seeds that have reached peak maturity and are at the point of natural dispersal. Practical recommendations for post-harvest handling of seeds were reported by Smith (1995) based on likely rates of viability loss under natural conditions using meteorological data pertaining to the region. The value of such data for planning purposes is illustrated again in this chapter. However, the availability of reliable and relatively cheap electronic devices for measuring both ambient conditions and seed moisture status means that practical recommendations can now be based on real-time measurements taken during collecting missions. The underlying principles of seed drying are also explained, together with practical approaches to low technology seed drying.

The design of drying facilities for seed banks is covered in detail elsewhere in this volume (Linington, 2003 – Chapter 33). A detailed description of the many different types of commercial seed dryers is beyond the scope of this chapter (for examples see Muckle and Stirling, 1971; Cromarty, 1984; Brooker *et al.*, 1992; Champ *et al.*, 1996, and references therein).

Moisture Equilibria and Seed Longevity

All seeds are hygroscopic, including those with impermeable seed coats, once the physical barrier has been breached. Seeds automatically absorb or desorb moisture by diffusion along a water potential gradient between the seed and the surrounding air. If the water potential of the seed is greater than the surrounding air, the seed will lose water and become drier. If the water potential of the seed is lower than the surrounding air, the seed will gain moisture. Absorption or desorption of water occurs until the water potential of the seed and the surrounding air is balanced. The moisture content of the seed at equilibrium is referred to as the equilibrium moisture content (eMC).

Knowing the moisture status of seeds is crucially important in seed conservation because seed moisture content (as well as temperature) determines the rate at which seeds lose viability and die. Thus the accurate measurement of seed moisture status is one of the most important routine tasks in seed conservation practice. Traditionally this has been achieved by gravimetric seed moisture content determination (International Seed Testing Association, 1985). However, an alternative, non-destructive method, is to measure the relative humidity (water vapour pressure/saturated water vapour pressure \times 100) of the air in equilibrium with the seed. In the last decade or so, instrumentation for measuring the equilibrium relative humidity (eRH) has improved significantly and this methodology is now used routinely in modern seed banks for monitoring seed moisture status (Probert *et al.*, 2003 – Chapter 20).

The equilibrium relationship between seed moisture content and RH at a given constant temperature is described by the reverse sigmoid curve of a moisture desorption or absorption isotherm (Figure 19.1a). The two points of greatest inflection on an isotherm delimit three distinct regions (I, II, and III) which indicate how the water is held in the tissue and hence its thermodynamic properties and the level of physiological activity which can occur (Leopold and Vertucci, 1986; Vertucci and Leopold, 1986, 1987a, b).

There are three principal types of water binding: water may be strongly bound at ionic sites e.g., charged carboxyl or amino groups of proteins, lipids, and cell walls (region I), weakly bound at polar, non-ionic sites (region II), or loosely bound through the bridging of hydrophobic moieties (region III). Loosely

bound water behaves as ‘bulk’ or ‘freezable’ water. All three types of water binding may be present at all moisture contents, although strongly bound water is predominant at very low moisture contents (region I) and bulk water is predominant at very high moisture contents (region III). In region I, where most of the water present is strongly bound, there is little physiological activity of any sort and seeds are in a relatively inert state. In region II, physiological processes, such as non-mitochondrial oxidation and chloroplastic electron transport, become evident. Finally, in region III, mitochondrial respiration and other normal metabolic processes commence (Vertucci and Leopold, 1986).

The exact shape of an isotherm depends on a number of factors (Figure 19.1a):

1. Temperature: for a given eRH, less water is absorbed at higher temperatures.
2. Whether the isotherm is one of absorption or desorption: due to the effects of hysteresis, slightly more water is present at a given eRH during desorption than during absorption.
3. Composition: seeds with a high oil content absorb less water, i.e., they have a lower equilibrium moisture content at a given RH.

Isotherms also appear to differ between seeds of the same species harvested at different stages of development, indicative of the changes in seed composition. For example, in muskmelon, at a given eRH, the moisture content of mature seeds is lower than that of less mature seeds (Welbaum and Bradford, 1989). Furthermore, isotherms differ between desiccation-tolerant tissues (e.g., mature orthodox seeds) and desiccation-intolerant tissues (recalcitrant seeds or immature seeds of orthodox species); desiccation-intolerant tissues appear to lack strongly bound, phase I water (Vertucci and Leopold, 1987b).

The water binding regions delineated by isotherms for orthodox seeds can be related to the moisture relations of seed longevity. The desorption isotherm with data points shown in Figure 19.1a is based on published data for yellow maize (Muckle and Stirling 1971). The Ellis/Roberts improved seed viability model (Ellis and Roberts 1980) applies to a seed moisture content range that corresponds with water binding region II (Roberts and Ellis, 1989). At moisture contents corresponding to region III, seeds are fully capable of repair, as long as they are hydrated, and it is well known that seeds that are more or less fully hydrated can survive for long periods (for example, Ibrahim *et al.*, 1983). If seeds are dried to very low moisture contents, corresponding to region I, there is either no additional benefit to seed longevity or, in the case of seeds that are not fully ripe, loss in viability may occur due to incomplete desiccation tolerance.

Over the moisture content range corresponding to region II, there is a negative linear relationship between the logarithm of seed longevity and the logarithm of seed moisture content. Consequently, although the range of seed moisture contents corresponding to region II is comparatively small (typically ~18 to ~5% depending on oil content), reducing seed moisture

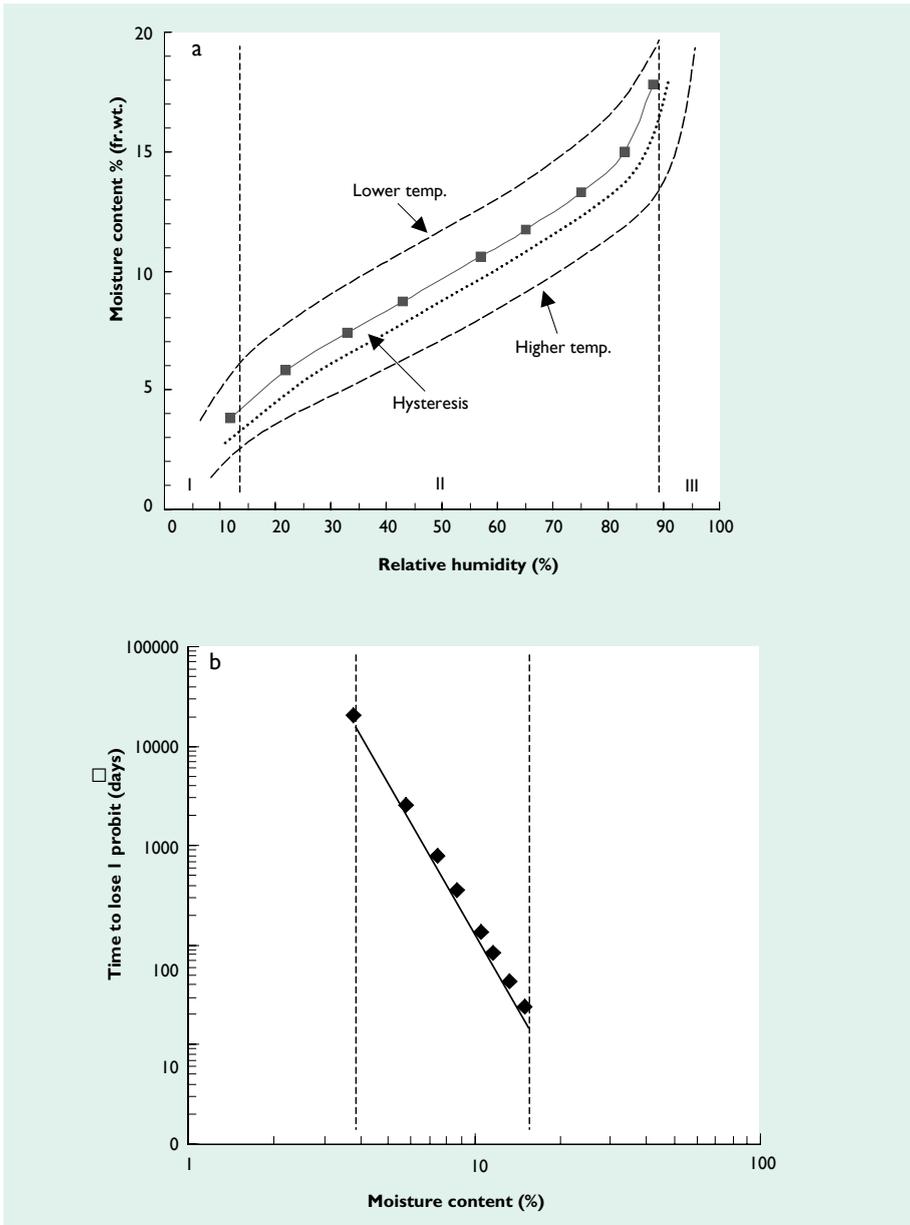


Figure 19.1 a) Desorption isotherm for yellow maize seeds [(solid line) adapted from data by Muckle and Stirling, 1971]. Dashed lines show the effect of lowering or raising the temperature on moisture equilibria. The dotted line illustrates an absorption isotherm and the phenomenon of hysteresis. Vertical dashed lines delineate the three water binding regions I, II and III. b) The logarithmic relationship between seed longevity and moisture content for yellow maize seeds stored at 25°C based on the isotherm data of Muckle and Stirling (1971). Vertical dashed lines correspond to the same moisture regions depicted in a).

content over this range has a considerable effect on potential seed longevity. Figure 19.1b shows the predicted longevity of yellow maize seeds calculated with the improved viability equation (Ellis and Roberts, 1980) using the data of Muckle and Stirling (Figure 19.1a). It is apparent that drying yellow maize seeds from seed moisture levels in equilibrium with typical ambient conditions (~80% RH) to the levels recommended for long-term seed conservation (15% RH) could be expected to result in an increase in seed life span of up to three orders of magnitude.

Seed Viability Loss Under Ambient Conditions

1. Predicting Viability Loss

For those species for which seed viability constants have been derived and seed oil contents are known, it is possible to estimate the rate of loss in viability of seeds held under ambient conditions using the following steps¹:

- a. Using published meteorological records (for example, HMSO, 1983), identify the temperature and RH values for the region and time of year of interest.
- b. Estimate the expected equilibrium moisture content of the seeds held under those conditions using the equation of Cromarty *et al.*, (1985):

$$M_e = [(1-D_o) \sqrt{-440 \times \ln(1-R)}] / [1.1 + (T/90)]$$

Where R = RH expressed as a proportion (not %); M_e = % equilibrium moisture content on a dr. wt². basis; T = °C temperature of the air and the seeds at equilibrium and D_o = seed oil content expressed on a dr. wt. basis as a proportion.

- c. The temperature and seed moisture content (on a fr. wt. basis) values can then be substituted into the improved viability equation of Ellis and Roberts (1980) along with the species constants K_E , C_W , C_H and C_Q , to estimate the rate of loss in viability, usually expressed as the time taken for viability to fall by one probit (for example 84–50% viability).

¹ A list of viability constants, seed oil contents and a macro to perform this procedure is available at <http://www.rbgekew.org.uk/data/sid/>

² fr.wt. moisture content can be calculated from dr. wt. moisture content by: $M_f = 100 \times M_d / (100 + M_d)$

Using this methodology the rates of loss in viability of maize seeds held under ambient conditions throughout the year at two contrasting locations in Kenya is shown in Table 19.1. The much faster loss in viability of seeds in Mombasa compared with Lodwar simply reflects the higher average monthly humidity at the coast compared to an inland dry arid area. The data makes the important point that humidity (and therefore seed moisture content) has a greater impact on seed longevity than temperature. Although Lodwar is clearly warmer than Mombasa, seeds die more slowly there.

Table 19.1 Predicted time for viability of maize seeds to fall by 1 probit (σ) under natural conditions of temperature and humidity at two contrasting locations in Kenya

	Lodwar				Mombasa			
	Temp (°C)	% rh	eMC	σ	Temp (°C)	% rh	eMC	σ
January	28.6	41.5	9.4	294	27.7	70	13.5	56
April	29.4	53	10.9	127	27.6	76.5	14.6	39
July	28.3	51	10.7	162	24.1	77.5	15.2	51
October	29.8	43.5	9.6	224	25.8	74	14.4	53

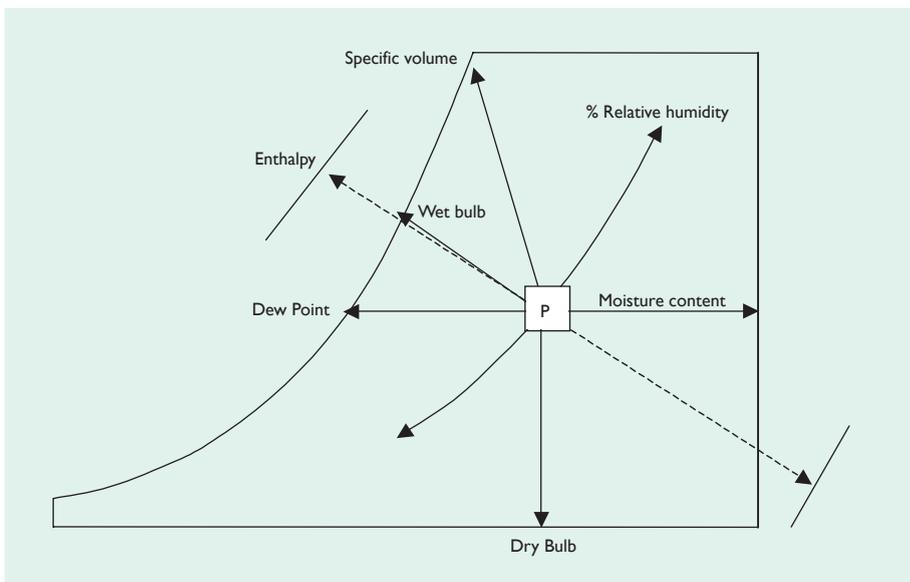


Figure 19.2 Diagram illustrating a psychrometric chart showing the read off positions for the seven psychrometric parameters relating to point P.

2. Introduction to Psychrometric Terms and Psychrometric Charts

In the previous section, the capacity of seeds to lose or gain moisture from the surrounding air was discussed simply in terms of the water potential difference between the seed and the air. There are in fact eight thermodynamic properties of moist air, seven of which can be estimated from so-called psychrometric charts (Figure 19.2). Otherwise known as *i-x diagrams* or *Mollier diagrams*, psychrometric charts are extremely useful in the design of seed dryers and for understanding the effects of local climatic conditions on seed viability thus informing post-harvest handling decisions.

Of the eight psychrometric terms, three are used to describe the amount of water vapour in the air: *vapour pressure*, *relative humidity* (shown as percent saturation) and *moisture content*. Three further terms refer to temperature: *dry-bulb*, *wet-bulb* and *dew-point temperature*. The remaining terms that are often used in seed drying calculations are: *enthalpy* and *specific volume*.

2.1. Vapour pressure

The *water vapour pressure* (P_v) is the partial pressure exerted by the water vapour molecules in moist air. When the water holding capacity of air is reached and the air is saturated with water molecules the water vapour pressure is referred to as the *saturated vapour pressure* (P_{vs}).

2.2. Relative humidity

Relative humidity (– percent saturation) describes the amount of water vapour held in the air as a percentage of the total amount of water that could be held at that temperature. It is the ratio of the water vapour pressure to the saturated water vapour pressure:

$$\% \text{ relative humidity} = (P_v/P_{vs}) \times 100$$

2.3. Moisture content

Often referred to as *humidity ratio* or *mixing ratio*. Not to be confused with seed moisture content, the *moisture content* is the mass of water vapour per unit mass of dry air and is usually expressed as kg (or g) kg⁻¹ dry air. This parameter can also be expressed as parts per million by weight (PPM_w). The terms are not the same as *absolute humidity* which refers to the mass of water vapour per unit volume of dry air (kg m⁻³) which in turn can be expressed as parts per million by volume (PPM_v).

2.4. Dry-bulb temperature

The *dry-bulb temperature* is the temperature of moist air as indicated by a conventional thermometer.

2.5. Wet-bulb temperature

The *wet-bulb temperature* is the temperature of moist air indicated by a thermometer, the bulb of which is covered by a wet wick. Because water will evaporate from the wet wick, causing a cooling effect due to the latent heat of evaporation, the wet-bulb temperature will be lower than the *dry-bulb temperature* except when the surrounding air is fully saturated (100% RH) when the wet and dry bulb temperatures will be the same. The difference between *dry* and *wet-bulb temperature* is dependent on RH and is the basis of the so-called *whirling hygrometer*.

2.6. Dew point temperature

The *dew point temperature* is the temperature at which condensation occurs, at the *saturated vapour pressure* or 100% RH, when air of constant water content is cooled and is the basis of so-called *dew point hygrometers*.

2.7. Enthalpy

The *enthalpy* of a dry air/water vapour mixture is the heat content of the moist air per unit mass of dry air above a reference temperature, usually expressed as kJ kg^{-1} .

2.8. Specific volume

The *specific volume* of moist air is the inverse of its density and is defined as the volume per unit mass of dry air, usually expressed as $\text{m}^3 \text{kg}^{-1}$.

The seven psychrometric parameters that can be read directly from a psychrometric chart are shown in Figure 19.2. Point P represents the psychrometric state of 1 kg of air at atmospheric pressure. For a more detailed description of the use of psychrometric charts in relation to grain drying systems, with worked examples and problems see Brooker *et al.*, (1992).

3. Using a Psychrometric Chart to Plot Environmental and Seed Viability Data

The environmental data for Lodwar and Mombasa shown in Table 19.1. are plotted as hatched areas M and L respectively on a psychrometric chart shown in Figure 19.3. The generally warmer and drier conditions of Lodwar are clear from the relative positions of the two areas. Also highlighted on the chart is the percent saturation or relative humidity curve for 30% RH. This has been chosen to represent a moisture level at or below which seeds would attain an equilibrium moisture content suitable for medium to long-term storage. The logic is as follows: Available evidence indicates that the optimum seed eRH for long-term storage is in the range 10–20% (for recent reviews of opinions on optimum moisture levels for seed storage see Hay and Probert, 2000; Walters, 1998; Walters and Engels, 1998). However, we know from seed isotherms that moisture equilibria are temperature dependent and therefore the eRH of seeds at a given moisture content will fall as temperature is lowered. Based on

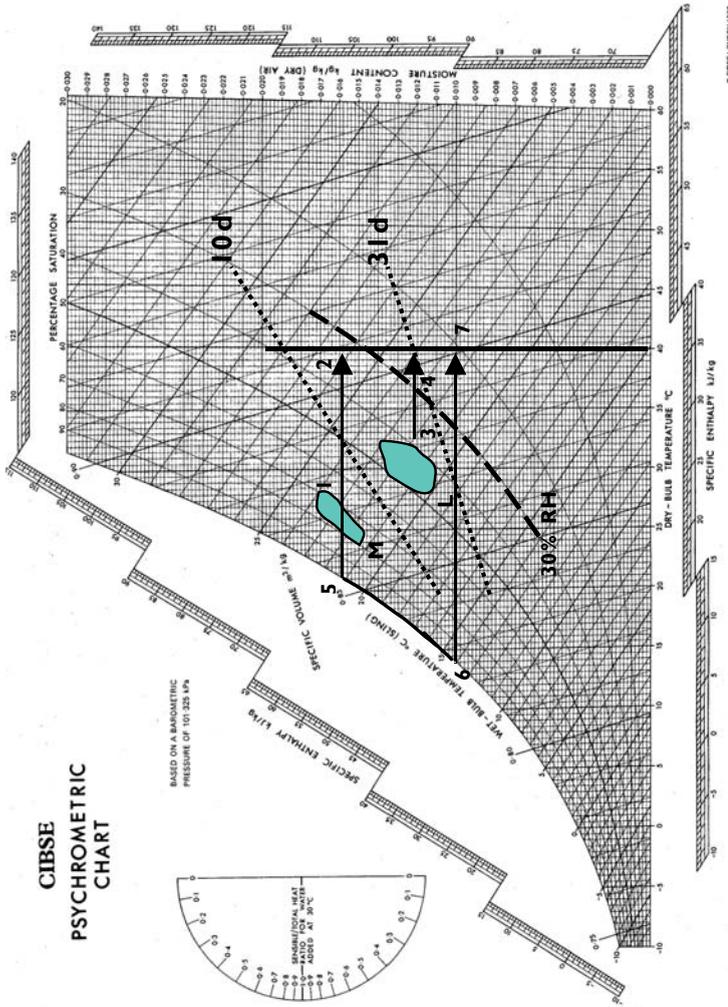


Figure 19.3 Psychrometric chart onto which seed longevity data for maize and environmental data for two locations in Kenya (Lodwar and Mombasa) have been plotted. Arrowed lines indicate the effect of warm-air drying in relation to the safe moisture zone for long-term storage. See text for detailed explanation. Psychrometric chart reproduced by permission of the Chartered Institution of Building Services Engineers. Copies of the chart are available from CIBSE, 222 Balham High Road, London, SW12 9BS.

the equilibrium moisture equation of Cromarty *et al.*, (1985), if maize seed were dried to 30% eRH at 40°C (the maximum temperature recommended for warm air drying of maize, indicated by the solid vertical line) the moisture content (fr. wt. basis) would be approximately 7.2%. If the seeds were then sealed with minimum headspace (see a following section) and cooled to 5°C the eRH would fall to approximately 18% – safely within the optimum range for medium to long-term storage at 5°C.

The two dotted lines represent combinations of temperature and humidity that would result in maize seeds losing 0.1 probits of viability in either 10 or 31 days. Both values have been chosen arbitrarily. However, the former, more rapid loss in viability might be considered an acceptable maximum if seeds were to be stored under local ambient conditions from one growing season to the next. Smith (1995) suggested the latter value as an acceptable rate of loss in viability under field conditions when collections were being made for long-term conservation. This rate is approximately 40 times faster than that which could be expected if seeds were held under seed bank dry room conditions (15% RH, 15°C).

Confirming the predicted rates of loss in viability of maize seeds held under ambient conditions at Lodwar and Mombasa (Table 19.1), it is clear that the humid conditions of Mombasa would result in unacceptable rates of loss in viability. By contrast the drier climate of Lodwar would maintain acceptable levels of seed viability from one growing season to the next. However, since all combinations of ambient temperature and humidity for Lodwar sit above the 0.1 probits in 31 days line, it is clear that the rate of deterioration under local conditions would not be acceptable for conservation collections.

The solid arrows marked 1–2 and 3–4 on Figure 19.3 represent the effect of heating air of typical moisture content at both locations to 40°C. The chart shows that warm air drying alone could achieve acceptable moisture levels for conservation purposes at Lodwar but not at Mombasa. At Mombasa, the moisture content of the air must be lowered. This can be achieved by cooling the air in a closed system. Point 5 on the chart represents the effect of cooling air with typical Mombasa water content to the dew point temperature. The line joining points 5 and 6 represents refrigeration drying where the water content is reduced from 0.16 kg kg⁻¹ to approximately 0.10 kg kg⁻¹. The line 6–7 represents the effect of warming this dried air to 40°C. At this temperature, the relative humidity of the air would be 20% and seeds dried to equilibrium under such conditions would achieve a moisture content close to the optimum for long-term conservation depending on storage temperature.

4. Guidelines for Immediate Post-harvest Handling and Drying of Seeds During Seed Collecting Missions

These guidelines assume that suitable instruments are available for measuring ambient conditions and seed moisture status.

4.1. Estimating the likely rate of seed deterioration under field conditions

As we have already seen, the moisture status of seeds and fruits of wild plants at the time of collection may be very high (Hay and Smith, 2003 – Chapter 6). Opportunities for lowering seed moisture to a safe level will depend on the prevailing ambient conditions. But at what temperature and seed eRH will the rate of deterioration be acceptable? Using Smith's suggested rate of 0.1 probits per month (Smith, 1995) and the methodology described above for maize, combinations of temperature and RH have been plotted onto a psychrometric chart for barley (*Hordeum vulgare* L.) (Figure 19.4). Barley is chosen here to represent an average seed. Based on viability estimates across 18 contrasting species at moisture contents in equilibrium with the same RH, the estimate for seeds of barley was closest to the average value (F.R. Hay pers. com.).

At all combinations of temperature and eRH below the line, the rate of seed deterioration can be considered acceptable (Figure 19.4). Conversely, at all combinations of temperature and eRH above the line, the rate of seed deterioration will be unacceptable and efforts must be taken to dry the seeds. This chart, which can be downloaded from: <http://www.rbgkew.org.uk/data/sid/>, can be used as a field guide to estimate the approximate rate of loss in viability of seed collections. Local prevailing temperature and seed eRH values can be plotted on the chart to inform post harvest handling decisions.

Note: it is recommended to use seed eRH rather than ambient RH in view of the likelihood that seeds will have not attained equilibrium. If eRH measurement is not possible, ambient RH should be used but with caution as seed eRH values are likely to be higher.

Previous studies have demonstrated a useful rule of thumb: seed longevity approximately doubles for every 10% reduction in RH (Roberts and Ellis, 1989). Thus it might be argued that any amount of drying will always be beneficial. However, we also know that hydrated seeds are reasonably long lived. Therefore it could also be said that there is little point in drying seeds unless they can be dried to a level where potential longevity is greater than that of hydrated seeds. But what is this level? Ibrahim *et al.*, (1983) reported that more or less fully hydrated lettuce seeds stored at 30°C took 200 days to fall in viability from 98–50%. Using published viability constants for lettuce (Kraak and Vos, 1987) and the equations of Ellis and Roberts (1980) and Cromarty *et al.*, (1985), we can estimate that at 30°C, the moisture content and eRH of seeds giving an equivalent rate of deterioration, would be ~8.4% MC, and ~60% eRH, respectively. Based on this very limited data, we could thus

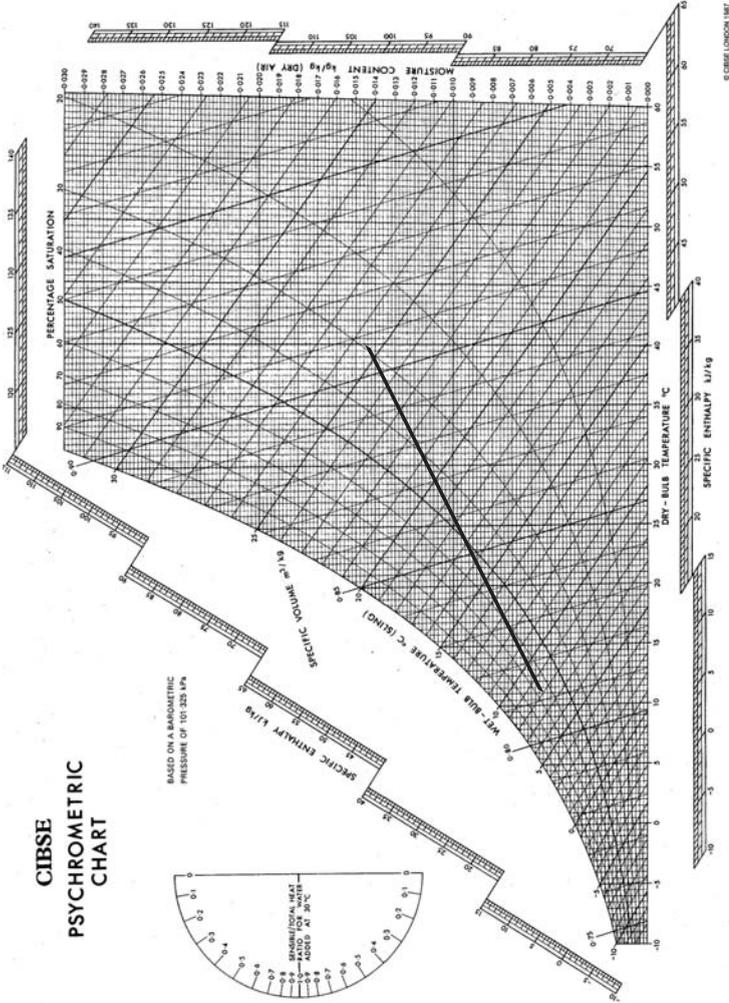


Figure 19.4 Combinations of temperature and eRH plotted on a psychrometric chart (denoted by solid line) causing viability of barley seeds to fall by 0.1 probits in 31 days. Temperature and RH combinations above or below the line would give unacceptable or acceptable rates, respectively, of seed deterioration during collecting missions.

argue that the potential drying environment must be capable of drying seeds to at least 60% eRH. However, Figure 19.4 shows that unless ambient temperatures were fairly low (around 15–16°C), eRH values around 60% would result in an unacceptable rate of seed deterioration. Assuming that ambient temperatures during seed collecting missions are more likely to be in the range 20–25°C, it seems reasonable to set 50% as an acceptable maximum relative humidity of the air if seeds are to be dried under ambient conditions.

4.2. Advice based on seed moisture status at the time of collection

Measuring the moisture status of seeds at the time of harvest need not require sophisticated, expensive instrumentation. Relatively simple, low cost, mechanical devices will enable seed collectors to identify the broad moisture categories described below (for more details see Probert *et al.*, 2003 – Chapter 20)

Wet seeds (100–85% eRH)

It would not be unusual for seeds at the time of collection to have eRH values in the range 100–85% (Hay and Smith, 2003 – Chapter 6). This might be due to a proportion of immature seeds within the collection but in many cases even fully ripe seeds at the point of dispersal can be at this level of hydration due to the humid microenvironment within open fruits following dehiscence. Above 90% eRH corresponds to moisture binding region III where cells contain sufficient free water for respiration and metabolic turnover provided oxygen availability is not limiting. Studies have shown that seeds can be reasonably long lived at such moisture levels because damage repair mechanisms are able to function. In practice this means that if seeds are collected at this moisture level and circumstances are such that it would not be possible to dry the seeds to a safe low moisture, it would be better to keep the seeds moist. This is best achieved by holding seeds in a partially ventilated container such as a loosely tied polythene bag. If this option is taken, it is crucial that the container is opened each day to allow air replacement for respiration and a check is made that the seeds are not becoming contaminated with micro-organisms. It is important to remember that at these moisture levels, seeds give off water as a by-product of respiration. Combined with the night-time rise in RH as temperature falls, this means that there is a risk that free water will form inside the container if it is, or becomes, air-tight. Controlling ventilation is therefore extremely important. If free water is evident, efforts should be made to reduce the significant risks of both mould infection and seed germination. In these circumstances the seeds should be dried off in open air until they are surface dry and then returned to the partially ventilated container. This approach is identical to the methods adopted for keeping desiccation sensitive seeds alive and is the basis for ripening treatments of immature seeds and fruits (see Hay and Smith, 2003 – Chapter 6).

Orthodox seeds are shortest lived at around 85–90% eRH. At this level, seeds are incapable of sufficient repair and damage accumulates rapidly leading to loss in viability. If seeds are in this state at the time of collection and if

conditions permit, it is very important that action is taken to dry the seeds as soon as possible. If conditions are not conducive to drying (ambient RH is similar to seed eRH) then the seeds should be kept moist using a ventilated container as described above, and as cool as possible, until suitable conditions for drying become available. If this option is taken, it is important to monitor ambient conditions so that the collection can be dried as soon as conditions become favourable.

When ambient conditions are favourable for drying (<50% RH) or where effective drying can be achieved using an air-conditioned room or with a desiccant such as silica gel, then seeds should be dried as soon as possible. When using ambient conditions, seeds should be spread thinly in a well ventilated position, held above the ground in the sun or partial shade. At night, seeds should be stored in sealed containers to prevent the absorption of moisture as the RH rises.

If the seeds are more or less fully hydrated (95–100% eRH) and silica gel is to be used, a very high silica gel to seed ratio (>5:1) will be needed to avoid the need for frequent replacement of the desiccant. Ideally, the seeds should be partially dried for 2–3 d under ambient conditions to remove the bulk water before using silica gel. This can be done even if the daytime ambient RH is relatively high (70–80%). Once the bulk water has been removed, the seed can then be transferred to a sealed container with silica gel. In this case, a silica gel : seed ratio of 1:1 will be adequate to reduce seed moisture to a safe level (~30% erh).

Relatively damp seeds (85–50% eRH)

In a survey of 30 species, including UK natives and tropical dryland plants, more than 85% had eRH values above 50% at the time of natural dispersal (see Hay and Smith, 2003 – Chapter 6). This underlines the importance of being able to measure the condition of seeds at the time of collection using appropriate instruments (see Probert *et al.*, 2003 – Chapter 20) and of taking appropriate action to dry seeds as soon as possible, when unacceptable rates of loss in viability are likely.

Relatively dry seeds (50–30% eRH)

From the foregoing discussion, it seems reasonable to set 50% eRH as an acceptable boundary where seeds at this level of hydration or less during a collecting mission could safely be kept in porous bags. However, care should be taken to transfer the bags to a suitable sealed container if the RH is likely to rise significantly, for example, at night, under open-air conditions.

Very dry seeds (<30% eRH)

During the dry season in many countries, the ambient RH during the daytime can drop below 30%. Clearly, collections of fully ripe seeds with moisture levels at the time of harvest <30% eRH will be safe from the risk of significant short-

term viability loss unless the prevailing temperatures are extremely high. For such collections, providing that any 'green' potentially moist material is removed and discarded, the seeds should be sealed immediately and kept sealed until the collection arrives at the seed bank or laboratory.

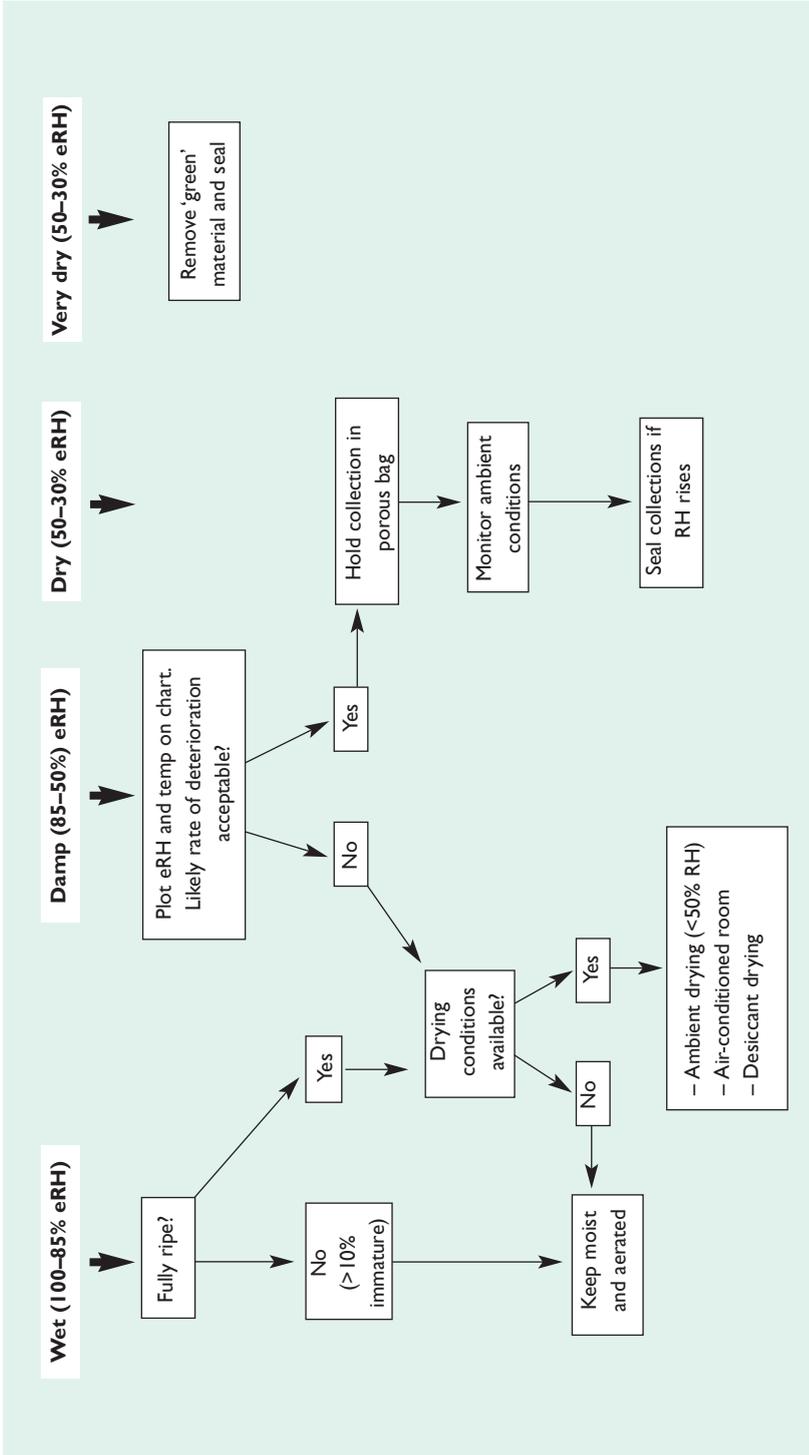
Seeds in Sealed Containers

The moisture holding capacity of air is directly related to temperature. We can visualise this on a psychrometric chart for air of a given water content as the increase or decrease in RH with increase or decrease in dry-bulb temperature. Thus the RH of the air inside an empty, sealed seed container will increase if the container is cooled. However, as discussed above, it is also clear from isotherms (Figure 19.1a) that if seeds of a given moisture content are cooled, the eRH will fall. This raises the important question as to what happens to the eRH inside a sealed container of seeds when the container is cooled from ambient conditions to sub-zero temperatures used for long-term storage. The answer is that it depends on the ratio of seeds to air-space in the container. If the container was very large and the amount of seeds was very small then an increase in seed moisture content may occur as the seeds equilibrate with the increased RH inside the container caused by the reduction in water holding capacity of the air. However, in practice, because efforts are taken to minimise headspace, the water content of the air will be so small compared to the water content of the seeds that the seeds will completely dominate the system. Consequently, the change in eRH will more or less follow that predicted by isotherms for seeds held at a constant water content but moved to a cooler temperature. Figure 19.5 illustrates these changes.

The reduction in eRH, possibly to sub-optimal levels, when seed collections held in sealed containers are cooled to sub-zero temperatures, was the central issue in the recent debate on optimum moisture levels for seed storage (reviewed by Hay and Probert, 2000; Walters, 1998; Walters and Engels, 1998). In summary, Walters and co-workers contend that if seed collections are dried to equilibrium at 15°C and 15% RH and then sealed and cooled to -20°C, the resultant seed eRH may be sub-optimal. Consequently, the dry room at the National Seed Storage Laboratory at Fort Collins, USA, operates at 23% RH and 5°C compared to the international recommended conditions of 10–15% RH and 10–25°C (FAO/IPGRI, 1994). A comparison of expected equilibrium moisture contents for seeds dried under the NSSL conditions or 15% RH and 15°C is shown in Table 19.2.

Decision making diagram for post-harvest handling based on seed moisture status at the time of collection

Box



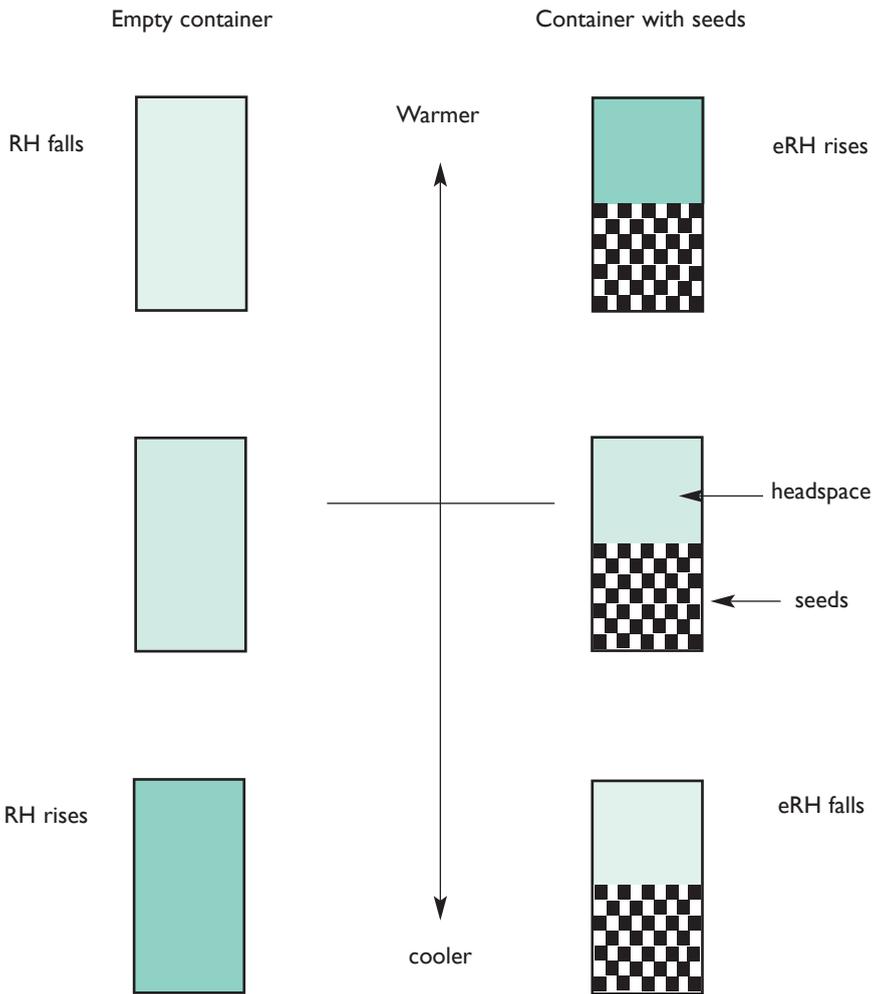


Figure 19.5 Diagram illustrating the effect on RH and eRH of warming and cooling sealed containers that are either empty or partly filled with seeds.

	USDA NSSL (23% RH, 5°C)	International standard (15% RH, 15°C)
Non-oily (2% oil)	8.3	6.1
Oily (35% oil)	5.7	4.2

At the Millennium Seed Bank, seed collections have been dried at 15% RH and 15°C for over 20 years. Viability retest data has shown no significant reduction in viability during this period in 86% of 2,388 collections. Based on this data, it has been decided to continue to adopt the international recommended conditions for the time being. Using short-lived species, experiments have been set up to compare the longevity of seeds dried to different equilibrium levels and then stored at sub-zero temperatures. When the results of these experiments are available (10–20 years time) or if similar data is published in the meantime, the MSBP drying protocols will be reviewed and adjusted, if warranted.

Seed Drying

1. Factors Affecting the Rate of Seed Drying

When drying occurs, water evaporates from the surface of the seed at a rate dependent on the water potential difference between the seed and the surrounding air. A water potential gradient is established between the surface of the seed and its internal tissues and water begins to diffuse along this gradient. As the seed approaches equilibrium with the surrounding air, the rate of drying slows down exponentially (Figure 19.6).

1.1. Seed size and structure

Seed size and the resistance of surrounding ‘seed coat’ structures have a marked effect on the rate of drying. Not surprisingly, large seeds dry relatively slowly compared with small seeds and increasing seed diameter results in a disproportionately longer drying time due to the extended internal moisture flow. Too-rapid drying of large seeds possessing porous seed coats can result in structural damage caused by the large moisture differentials established between the surface and internal layers of the seed. In some cases, this can lead to a collapse and shrinkage of the seed coat, resulting in the formation of a permeability barrier. Consequently, drying may be arrested, thus increasing the risk of viability loss due to ageing (Stubsgaard and Poulsen, 1995).

1.2. Air velocity

In a closed system with no air movement, the RH of the air surrounding seeds will rise as they lose moisture. As a consequence, the rate of drying will slow down and eventually stop. Ventilation will help to maintain the water pressure gradient and ensure that drying proceeds. Optimum drying will be achieved in an open system with air movement. As an approximation, drying time is halved when the velocity of the surrounding air is doubled.

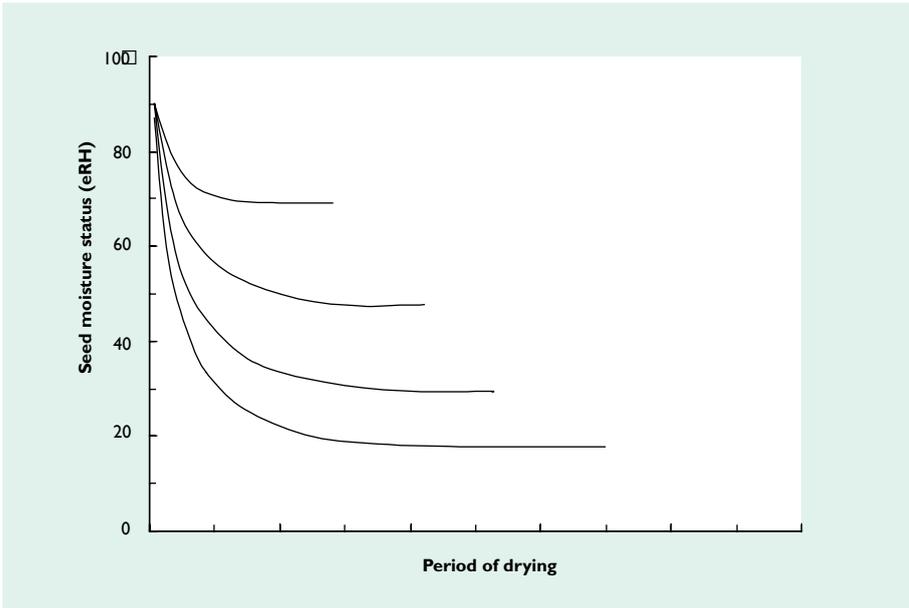


Figure 19.6 Hypothetical curves for seeds drying to different equilibrium values. The rate of drying slows down exponentially as seeds approach equilibrium. The further the seeds are from equilibrium at the start of drying, the longer the drying time.

1.3. Temperature

The water-holding capacity of air is temperature dependent. Consequently, at a constant moisture content, the RH of the air decreases with increases in temperature. In practice, the rate of diffusion of water from the surface of seeds, and hence the speed of drying, is determined by the vapour pressure deficit which can be measured by the difference between the RH of the air and the eRH of the seeds. Water also evaporates more quickly at higher temperatures and therefore raising the temperature will always accelerate drying; a 10°C increase in temperature approximately doubles the rate of drying. Not surprisingly, high temperatures are usually employed to dry crop seed. Although the use of high temperatures carries the attendant risk of accelerated seed ageing and hence viability loss during the drying process, seed temperature is offset during the drying process due to the latent heat of evaporation. This process is often referred to as psychrometric cooling.

In large-scale, crop seed drying, economic considerations drive the choice of conditions and some viability loss or seed damage during drying might be acceptable, especially if the seeds are not required for planting. Bulk-drying is complex because, in addition to the factors already described, the rate of

drying depends on the depth of the seed bed and the rate of air movement through it. Ageing-related losses may occur during bulk drying if the rate of drying is slow and seeds are exposed to warm conditions while still moist. Indeed, if the seeds are very moist, heat leading to loss in viability could build up in the seed layers due to respiration.

When seeds are processed for conservation purposes, it is imperative that no seeds are unnecessarily lost during drying. Consequently, low temperature drying methods using artificial desiccants are usually employed to minimise viability loss. For example, the recommended drying conditions for seed conservation are 10–25°C and 10–15% RH (FAO/IPGRI, 1994).

To predict seed drying times, Cromarty developed a Seed Drying Nomogram (Cromarty *et al.*, 1985) which draws together into a single chart the primary factors (described above), which affect the optimal drying of seeds when they are spread out into a single layer ('thin-layer drying').

2. Low Technology Seed Drying

2.1. Sun/shade drying

For thousands of years, humans have successfully exploited the combined effects of solar heating and ventilation by the wind, as a means of drying seeds, and to this day, sun-drying is widely adopted in many countries for small scale seed-drying.

Sun drying is traditionally applied to seed after threshing, usually by simply spreading seeds in a thin layer on a sealed surface such as a road from which they can be easily retrieved (Tumaming, 1988; Lantin *et al.*, 1996).

There are, however, two principal drawbacks to sun-drying:

1. Overheating: Prolonged direct exposure to the sun may cause seeds to overheat resulting in loss of viability due to ageing, or physical damage due to cracking. To reduce this risk, regular turning of the seeds by raking can be employed and/or seeds can be shaded by a suitable screen.
2. Erratic drying: By definition, 'sun-drying' implies that seeds are exposed to the natural vagaries of the climate. During the dry season, sun-drying can be a realistic and predicable option. However, attempting sun-drying during the wet season carries the risk that drying will at best be interrupted during wet weather and possibly reversed if measures are not taken to cover the seeds. Even during the dry season, a similar problem arises at night due to the fall in temperature and consequent increase in RH. For this reason, it has been recommended that, if possible, seeds undergoing daytime sun-drying should be transferred to sealed containers at night (Prendergast *et al.*, 1992).

To promote the continuation of drying of seeds at night-time, solar heat can be 'stored' as drying capacity in desiccants such as silica gel (Aldis *et al.*, 1978) or corn (Bern *et al.*, 1979). Essentially, the desiccants are regenerated during the day in the sun and then used to maintain seed drying at night in sealed containers.

Modern demands for wet- and dry-season rice production in developing countries in SE Asia has led to an inevitable trend away from traditional sun drying towards modern mechanised methods. However, the potential economic and environmental benefits of sun-drying has prompted research into a variety of options to overcome its inherent problems (Lantin *et al.*, 1996).

In a recent study conducted in Kenya, comparing the effects of sun, shade and dry-room drying on the quality of *Milletia leucantha* Vatke seeds collected at different stages of maturity, Muthoka *et al.* (2003 – Chapter 7) showed that neither sun or shade drying were detrimental to seed quality. Indeed, in this particular study, seeds dried in a dry room at 15% RH, and 15°C were of consistently poorer quality, probably the result of poor ventilation during drying and hence a longer drying period.

2.2. Artificial desiccants

There is a range of commercially available hygroscopic substances useful for drying seeds including: silica gel, molecular sieves, lithium chloride, calcium chloride and drierite (CaSO₄). Although silica gel is the most commonly used desiccant for small samples of seeds held in sealed containers, any hygroscopic substance can be used to remove moisture from seeds providing that the eRH of the desiccant under given conditions is lower than the eRH of the seeds. Indeed, seeds themselves are an excellent desiccant – hence the common practice of using rice grains to keep salt dry in salt cellars – and seeds are particularly useful when other options are not available. For example, toasted rice has been used successfully to dry a variety of seeds including those of potato, tomato, pepper, lettuce, turnip, and soya bean (Sadik and White, 1982), cowpea, eggplant, lima bean, okra, and rice (Akromah and Bennett-Lartey, 1996). Other widely available and potentially cheap desiccants for seeds include clays such as bentonite (Srivastava and Bilanski, 1981; Sturton *et al.*, 1981, 1983) and charcoal.

Charcoal as a low-cost desiccant

Previously unpublished work in our laboratory investigated the water absorption characteristics of charcoal from a variety of sources to assess whether this universally available (and cheap) product could be used as an effective seed desiccant. Coarse and sieved charcoal was oven dried to remove all moisture and then allowed to rehydrate slowly by moving to different controlled environments at room temperature (21°C). For all batches of charcoal investigated there was a linear relationship between moisture content (f. wt. basis) and relative humidity (Figure 19.7). Analysis of deviance showed that isotherms for graded and coarse charcoal could be constrained to a single

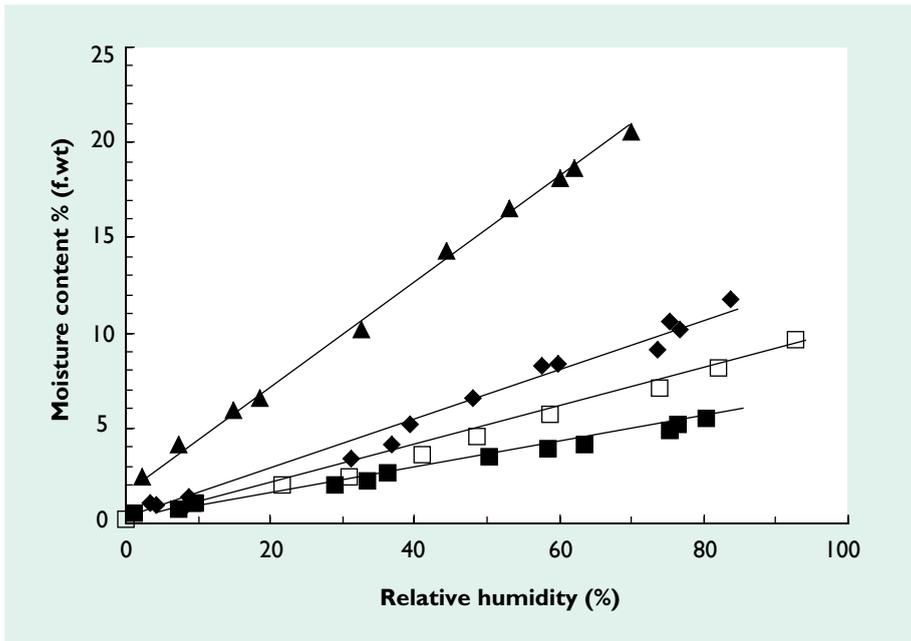


Figure 19.7 Isotherms for silica gel (▲) and three different batches of charcoal at 21°C. Square symbols (■ □) represent batches of charcoal produced at Wakehurst Place from UK native hardwood species in two consecutive years. The diamond symbol (◆) represents charcoal produced in Brazil from the tree *Piptocarpha angustifolia* Dusén ex Malme.

regression confirming that water absorption characteristics were not affected by particle size. However, isotherms for charcoal from the same source but produced in different years and isotherms for charcoal produced from different trees had significantly different slopes ($P < 0.05$).

Variation in water absorption between different batches of charcoal should not detract from the potential use of this material. Indeed, silica gel is known to vary both between batches and within the same batch after repeated cycles of regeneration. For example, an adsorption isotherm produced in our laboratory for silica gel had a slope value of 0.2699. That is to say the water holding capacity increased by 0.0027 g of water per g of dry silica gel for every 1% increase in RH. This compares with a value of 0.0066 reported previously by Cromarty *et al.*, (1985).

The isotherms presented here (Figure 19.7) reveal that charcoal is an inferior desiccant compared to silica gel. However, the fact that charcoal is universally available and inexpensive, particularly in dryland countries, makes its potential use realistic particularly at the community level. As with all desiccants, users would have to ensure that charcoal is completely dry before

using it as a desiccant for seeds. This could be achieved simply by baking the charcoal at a low heat in a simple oven. After drying, the charcoal should be allowed to cool and then used for seed drying as soon as possible. Seeds, spread in a thin layer, should be dried over a bed of charcoal held inside a suitable sealed container.

Calculating the amount of desiccant required

In the following example, it is assumed that non-oily seeds (oil content 2%) will be dried from a moisture content in equilibrium with 80% RH to a moisture content in equilibrium with 30% RH. Although 30% eRH is above the moisture level recommended for long-term seed conservation, this moisture level can be regarded as an acceptable maximum when the lack of facilities may preclude drying to lower levels.

The equilibrium moisture content of seeds at a given RH can be calculated using the equation of Cromarty *et al.*, (1985) as described earlier. Converting to fr. wt. moisture content, the eMCs of non-oily seeds at 80% and 30% rh at 25°C are estimated to be 15.9 and 8.2 respectively.

The weight of water (w) to be removed by drying can be calculated using the equation:

$$w = M(mc_i - mc_f) / 100 - mc_f$$

where M is the starting fresh weight of the seeds, mc_i is the initial moisture content and mc_f is the final moisture content.

Using the equation above the weight of water to be removed from 1kg of seeds during drying would be:

$$w = 1 (8.2 - 15.9) / 100 - 8.2 = 0.084 \text{ kg}$$

From an average value of the slopes (0.0989 i.e., 0.000989 kg H₂O kg⁻¹ fruit % RH⁻¹) of the isotherms for charcoal presented in Figure 19.7, a typical moisture content (fr. wt. basis) for charcoal at 30% rh can be estimated as:

$$30 \times 0.000989 = 0.02967 \text{ kg H}_2\text{O kg}^{-1} \text{ charcoal}$$

Therefore the fr. wt. of charcoal needed to hold the water removed by drying would be:

$$0.084 / 0.02967 = 2.83 \text{ kg}$$

$$\text{or } 2.83 - 0.084 = 2.75 \text{ kg of dry charcoal.}$$

Rounding up, we can say that a weight ratio of moist seeds (assuming that bulk water has been removed and a starting eRH ~80%) to dry charcoal of 1:3 would be adequate to dry seeds to a moisture level that would allow medium- to long-term storage.

Running the same calculations for seeds to be dried to the international recommendation for long-term conservation (15% eRH) increases the weight of dry charcoal to 7.3 kg or, again rounding up, to a 1:7.5 ratio of seeds to charcoal.

Using the same approach and the isotherm data for silica gel presented in Figure 19.7, the corresponding ratios for silica gel drying to 30% eRH and 15% eRH would be 1:1 and 1:4, respectively.

Conclusions

Depending on the prevailing humidity and temperature at a particular location, the rate of loss in viability of seeds held under field conditions may be unacceptable. Meteorological data, or direct measurement of ambient conditions, can be a useful guide to the probable effect of ambient conditions on seed quality and to the likelihood or otherwise of suitable conditions for field drying. However, such data does not take into account the high probability that the moisture status of seeds at the time of collection will be significantly higher than the prevailing relative humidity of the air. As a result, there is a high risk that the rate of deterioration under field conditions for the majority of collections made during a mission will be unacceptable.

Direct, real-time measurement of the moisture status of seed collections at the time of harvest is strongly advocated and instrumentation for measuring seed eRH is described in the following chapter by Probert *et al.* Seed eRH and ambient temperature values can be plotted onto a psychrometric chart to inform post-harvest handling decisions.

When the ambient RH is 50% or less, seed collections can be dried effectively in the field and it will be safe to hold collections in porous bags during transit. However, precautions must be taken to avoid moisture uptake as the RH rises during the night.

When ambient conditions are not suitable for seed drying and when air-conditioned facilities are not available, artificial desiccants such as silica gel or even charcoal can be used. As a general guide, seed : desiccant ratios of 1:1 or 1:3 respectively for silica gel and charcoal will reduce seed moisture to levels suitable for medium to long-term storage, provided that bulk water has been removed by initial drying under ambient conditions.

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