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ISSN 0952 8245
Bulletin No.21

ODNRI

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OVERSEAS DEVELOPMENT NATURAL RESOURCES INSTITUTE
BULLETIN

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THE PHYSICAL EFFECTS OF TROPICAL HUMID SEASONS ON BAGSTACKS OF GRAIN

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PUBLISHED BY

ODNRI

THE SCIENTIFIC UNIT OF THE
OVERSEAS DEVELOPMENT ADMINISTRATION

This bulletin was produced by the Overseas Development Natural Resources Institute which was formed in September 1987 by the amalgamation of the Tropical Development and Research Institute and the Land Resources Development Centre. ODNRI is the scientific unit of the British Government's Overseas Development Administration and is funded from the overseas aid programme. The Institute provides technical assistance to developing countries and specializes in the utilization of land resources, pest and vector management and post-harvest technology.

Price £7. 20

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Overseas Development Natural Resources Institute
ISBN 0 85954 243-2
ISSN 0952 8245

Contents

Summaries

SUMMARY

Moisture diffusion into stacks of grain in sacks in tropical climates was studied. Wheat was used for a laboratory trial in simulated humid conditions, and millet and milled rice stacks were examined in warehouses in savannah and hot humid climates respectively. The measured moisture ingress profiles generally agreed with the predictions of a theory of isothermal moisture diffusion.

RESUME

La diffusion de l'humidité dans des piles de sacs de grains en climat tropical a fait l'objet d'une étude. Le blé a servi pour une expérience en laboratoire dans des conditions d'humidité simulées, tandis que le millet et le riz usiné ont été étudiés dans des entrepôts se trouvant respectivement en climat de savane et en climat chaud et humide. Les profils d'admission d'humidité mesurée étaient généralement en accord avec les prédictions d'une théorie de diffusion isotherme de l'humidité.

RESUMEN

El artículo examina la difusión de la humedad en grano ensacado y apilado, en climas tropicales. Se utilizó el trigo para una prueba experimental bajo condiciones húmedas simuladas, mientras que el mijo y arroz molido apilados fueron examinados en almacenes de climas de sabana y climas cálidos y húmedos, respectivamente. En términos generales, las tónicas de ingreso de humedad medidas estuvieron de acuerdo con las predicciones de una teoría de difusión isotérmica de la humedad.

The physical effects of tropical humid seasons on bagstacks of grain

INTRODUCTION

In grain storage the relative humidity of the intergranular air is an important physical factor because it can influence the growth of mould. All grain is infected with moulds, and if the r. h. exceeds 70% the grain becomes susceptible to mould damage, the rate of spoilage being also affected by the temperature. The r. h. of the intergranular air is usually in equilibrium with the moistrue contained in the grain, and in this condition is commonly known as the equilibrium relative humidity. (e.r.h.). When the r.h. of the air surrounding a quantity of grain is higher than the e.r.h. the water vapour pressure differential induces diffusion into the grain bulk. Pixton and Griffiths (1971) investigated this process using small columns of wheat and obtained satisfactory agreement with a theoretical model based on Crank (1956); changes in moisture content (mc) at a distance from the grain surface are given by the equation:

$$\Delta\, mc_t = 100\, \Delta\, mc_\infty \left(1 - \mathrm{erf}\frac{X}{2\sqrt{Dt}}\right) \qquad \text{.........(1)}$$

where X = distance normal to the surface;

$\Delta\, mc_t$ = increase in moisture content, dry-weight basis, at X after time, t;

$\Delta\, mc_\infty$ = increase in moisture content, dry-weight basis at infinite time;

D = constant of proportionality, defined as the coefficient of diffusion.

Tabulated values of the error function,

$$\mathrm{erf}\, Z = \frac{2}{\sqrt{\pi}} \int_0^z e^{-\eta^2} d\eta$$

are given by Crank (1956) and others.

MATERIALS AND METHODS

Stacks and their environments

For the laboratory trial, an English variety of soft wheat initially at 40% e.r.h. 10% mc* and 27 °C, packed in 100 kg jute sacks, was built into a nearly cubic stack comprising 5 layers of 5 sacks. The r.h. and temperature of the air in the test laboratory were 75 ± 5% and 27 ± 2 °C respectively; the trial lasted 4 months.

The savannah climate trial was carried out at Segou, Mali, 13° north, 6° west, altitude 300 m. A local red variety of millet initially at 41% e.r.h.

*Moisture content values are wet-weight basis unless stated otherwise.

(estimated from the mc), 9% mc and 33 °C in 100 kg jute sacks was built into a 180 tonne stack, 9 m long, 6 m wide and 4.5 m high in a 10-year-old warehouse. The warehouse was 60 m long, 25 m wide and 4.5 m from floor to eaves. It was constructed with concrete walls and floor and had a corrugated galvanized-iron pitched roof on steel girders. The warehouse was well ventilated through louvred vents below the eaves along the long walls. The condition of the stack was monitored for 14 months through two humid seasons.

The humid climate trial was undertaken in Colombo, Sri Lanka, 7° north, 80° east, altitude 10 m. A local variety of milled rice, initially at 60% e.r.h. (estimated from mc), 13.3% mc and 32 °C in 77 kg sacks, was built into a 100-tonne stack 6.3 m long, 5.8 m wide and 3 m high, inside a 20-year-old warehouse. The warehouse was 30 m long, 24 m wide and 5.5 m high from floor to eaves. It was constructed of brick 240 mm thick, with a concrete floor. The roof was a corrugated galvanized-steel construction with some transparent sheets for lighting. Ventilation was provided by narrow permanent openings at the eaves and ridge. The condition of the stack was monitored for 12 months through two humid seasons.

MONITORING PHYSICAL CHANGES

Ingress of moisture and changes in temperature during the trials were monitored with Reethorpe sensors (Gough, 1980) and thermocouples respectively. They were installed in the stacks at the time of building. Most Reethorpes were positioned in groups on Perspex holders near stack surfaces where significant changes were expected. Reethorpes on the surface were exposed to large moisture content gradients. In these conditions the electrical current passed through the sensor cell grain from the central rod almost exclusively through the wetter side to the perforated barrel. The 'position' of the sensor was therefore deemed to be the point half-way between the rod and the wetter side of the barrel.

A thermocouple was fixed against each Reethorpe partly because it was essential to know the temperatures of the Reethorpes in order to deduce mc values. Since large changes were not expected in the interior of the stacks, only a small number of Reethorpes and thermocouples were installed there. It was anticipated that the physical presence of the Reethorpes and holder would distort the moisture ingress profile. To prevent this affecting mc readings the Reethorpes in their holders were located in a line at a orientation of 30° to the stack surfaces. Figure 1 shows the sensor positions on a holder in a central vertical plane through the laboratory bagstack. The number of holders installed in the wheat, millet and rice stacks were 3, 6 and 6 respectively.

Identical considerations were applied to the sensor installation in all three trials. Full sets of readings from the sensors were collected at 3- and 7-day intervals during the laboratory and field trials respectively. There was a 7-week break in data collection in the middle of the savannah climate trial.

In the field trials, temperature and humidity conditions inside and near the warehouses were monitored with thermohygrographs. More detailed ambient data were obtained from the nearest meterorological stations and it was these data that were used in the predictive calculations.

RESULTS

Laboratory trial

In the laboratory trial the temperature of the stack ranged from 25.5 °C to 28.5 °C. Moisture content increased with storage period and proximity to the stack surface – increases were 3% or more to a depth of 60 mm after 60 days' storage which extended to 100 mm after a further 60 days.

Savannah climate trial

Weather conditions during the Savannah climate trial were close to those during the corresponding months recorded for the previous 8 years. Ambient temperature ranged from a monthly mean of 33 °C in June to 25 °C in December (*see* Figure 2) and mean r.h. varied from 80% in August to about 25% in March (*see* Figure 3). Temperatures in the stack changed only slowly (*see* Figure 2). At the stack centre, maximum and minimum recorded temperatures were 39 °C and 31 °C respectively, while at the sides of the stack the corresponding values were 39 °C and 20 °C. Seasonal temperature changes in the stack centre lagged behind the ambient average values by about 3 weeks. There was no significant long-term stack heating or cooling.

Moisture content of the grain changed according to the length of storage, the season, and the depth in the stack (*see* Figure 4). Recording began in the last third of a humid season, and mc initially rose. It reached peak values first at the stack surface and progressively later deeper in the stack. The increase was, for example, 3.5% above the initial value of 9% at a depth of 50 mm (*see* Figure 4). A decline then occurred generally during the following dry season. The minimum mc reached could not be measured because the meter used with the Reethorpe sensors was unreliable below about 8.5% mc. The drying-out pattern appears to have been similar to the wetting-up one – deeper in the stack the mc decreased more slowly. At the onset of the second humid season the mc near the stack surface increased again and reached a peak 4.5% above the dry season recorded minimum of 8%. Again, deeper in the stack the increase in mc began later and rose by only 1% to 2% at depths of 200-250 mm. During the last two weeks of the trial a small decline in surface mc took place.

Humid climate trial

Weather conditions during the humid climate trial were similar to those averaged over a 30-year period. Ambient temperature ranged from a monthly mean of 28 °C in August and April near the beginning and end of the trial respectively and 26 °C in January (*see* Figure 5). Humidity ranged from a monthly mean of 82% r.h. in September to 70% r.h. in January (*see* Figure 6).

Stack temperature changes were slow and much less than in the Savannah climate trial; the maximum and minimum temperatures at the centre were 33 °C and 30 °C respectively, and the corresponding values at the sides were 32 °C and 27 °C. As in the Savannah climate trial, seasonal temperature changes at the stack centre lagged behind those at the sides by 3 weeks and there was no significant stack heating or cooling.

Moisture content changed according to the length of storage, the season and the depth in the stack. Recording began in the second half of a humid season and mc initially rose at and near the stack surface (*see* Figure 7). It reached a peak of 2% above its initial value of 13.3%. A decline then took place in the following dry season reaching a minimum of 12.5%. Deeper in the stack changes were similar but reduced in magnitude and slower; for example, at a depth of 100 mm the mc increased during the first humid season by only 0.5%. The second humid season raised the stack surface mc from the low point of 12.5% up to 16.5%. As before, deeper in the stack the response was smaller and slower; for example, at a depth of 100 mm the increase was only 1% mc.

DISCUSSION

Laboratory trial

Since the thermocouples showed no significant temperature differentials across the stack in the laboratory trial it was assumed that only negligible mc changes took place in the stack due to non-isothermal moisture diffusion, convective airflow or insect or mould infestation. The moisture diffusion theory was developed to predict planar diffusion. In order to apply it to the surface of a bagstack it had to be modified. In this modified form and using equation (1) changed to include mc values defined on a wet-weight basis it predicted mc values which were generally similar to the measured data. For example:

for t = 120 days of storage
D = 10.5×10^{-10} m^2/s (obtained from Pixton and Griffiths, 1971)
mc_{∞} = 15%

the equation produced the line shown in Figure 8. The corresponding mc values from the readings of six Reethorpes on one of the Perspex holders are also shown. It can be seen that there is some agreement between the predicted line and the measured data. Similar agreement was obtained for the other Reethorpes and for other days of storage. The effectiveness of equation (1) to predict measured data can be assessed by determining the percentage residuals. This is a statistical parameter which expresses the proportion of the measured changes which are predicted by equation (1) after a specific period of storage. It is defined as follows:

$$\text{percentage residuals} = \frac{\Sigma(x - \hat{x})^2}{\Sigma(x - \bar{x})^2} \times 100\%$$

where x = value predicted by equation (1) corresponding to the measured value

$\hat{x}$ = measured value from one Reethorpe after a specific period of storage and at a specific depth in the stack

$\bar{x}$ = mean of measured values at various depths e.g. the values from six Reethorpes in one Perspex holder

Table 1 shows that approximately 90% of the change in measured values after 120 days of storage can be predicted by equation (1).

Table 1

Percentage residuals after 120 days of storage

	Percentage residuals
All sets	89.5
Set on holder A	90.0
Set on holder B	82.3
Set on holder C	95.1

Note: The holders were located in the sides (A and B) and top (C) of the stack

The differences between measured and predicted data for the three sensor sets declined with time, and after 70 days of storage were relatively small. The predictive power of the theory also improves with depth from the stack surface. The theory is potentially most effective in predicting conditions after several months of storage, which is when it is most useful. Figure 9 shows the differences between observed data from all the sensors and the corresponding predicted values, during the fourth month of storage, and it illustrates the scatter in the observed data. The prediction is reasonably good, but the differences are not randomly distributed. There is a correlation between residuals and period of storage at a given stack depth, and over stack depth at a given period of storage. The possibility that this systematic behaviour may arise from errors in the parameters or measurement error has been investigated.

The largest potential errors in predictions by equation (1) could arise from the following sources:

- **mc_{∞}** An error of ± 0.5% mc in the estimated mc_{∞} would lead to errors in the theoretical mc which increased with increasing storage period, amounting to between ± 0.2% and ± 0.5% mc after 120 days of storage, decreasing with depth;

- **measurement of depth** An error of ± 5 mm in the measured location of a Reethorpe would lead to errors in the theoretical mc which decreased with increasing storage period, amounting to between ± 0.1% and ± 0.15% mc after 120 days of storage, decreasing with depth;
- **monitor readings** The bias in any individual Reethorpe reading lies in the range ± 0.7% mc in 95% of a population of Reethorpes (Gough, 1980). This would lead to residuals which were constant over time for each sensor, but varied between sensors in the range ± 0.7% mc.

In practice it seems likely that these factors have interacted to produce the systematic differences exhibited between the predicted and measured data.

Savannah climate trial

Prediction was less successful for the savannah climate trial. Predicted mc was calculated using equation (1) for the second humid season from the 243rd to the 419th day of storage, because during this time the observed mc rose significantly. Data from malfunctioning sensors and from those at the bottom of the stack (where only limited moisture change would be expected) have not been included in the comparison with predicted mcs. Equation (1) assumes (Pixton and Griffiths, 1971), (i) uniform initial mc, (ii) constant external humidity, and (iii) planar moisture diffusion. However, at the start of the second humid season, mc varied thoughout the stack; external humidity rose over time; diffusion of moisture was non-planar due to the curvature of the sacks, and the close weave of the sack material may have attenuated moisture ingress. Initial observed mc of each sensor was taken to be the reading at day 243, except where this reading was much above that in the period immediately following. This occurred for some sensors in the stack interior and then the minimum reading was taken. mc_{∞} was assumed to vary with external humidity from 8% to 13.6% from the 243rd to the 398th days of storage respectively.

There was reasonable agreement between observed and predicted values; some 70% of the observed values were explained by equation (1) and this rose to 83% if allowance was made for possible sensor bias (Gough, 1980). Comparison of goodness of fit (i.e. the extent of agreement between observed and predicted values) for individual sensors showed that for those 30 mm to 220 mm below the stack surface, there was good agreement. Figure 10 shows observed and predicted mc over time for a typical sensor. This one was at a depth of 50 mm from the stack surface. There were however two groups of sensors which showed systematic disagreement with predicted values:

(i) sensors deep in the stack (at depths greater than 400 mm) showed small increases in mc where none was predicted;

(ii) sensors at depths of about 200 mm showed a fall in mc in the early part of the second humid season, and did not show an increase in some cases until after 340 days of storage.

Both of these discrepancies may be due, at least in part, to the variation in mc throughout the stack at the onset of the second humid season, and humid air drawn by convection into the stack through the inter-bag voids. At some depth within the stack, moisture from the previous humid season had not dried out, creating a 'hump', so that at the same time as external humidity rose and moisture diffused in from the surface, it also diffused radially out from the hump. (*See* Figures 11 a – d).

When observed and predicted mcs were plotted against depth at the end of the second humid season it was found that the differences were mostly positive; that is, the predicted mc tended to underestimate the observed mc.

Further evidence of this is shown in Figure 12. For operational reasons the experiment began well into the first humid season, so that the absolute increase is somewhat less than in the second humid season. In both cases, for depths greater than 150 mm, the increase in mc is underestimated.

Humid climate trial

Compared to the savannah climate trial, prediction of observed data during the humid climate trial was generally equally effective (*see* Figures 10 and 13). The humid trial was a less rigorous test of the theory because the mc changes were only half of those in the savannah climate trial. For operational reasons the trial could only begin in the middle of a humid season. Prediction during the first humid season was good (*see* Figure 14), but inconclusive during the second humid season because there was little increase in the observed measurements. Also, the readings indicated considerable scatter. This would again appear to be due to the presence of a first humid season moist zone or 'hump' deep in the stack diffusing out during the second season (*see* Figures 15 a – d).

CONCLUSIONS

1. The amount of moisture which diffuses into bagstacks of grain stored in warehouses during tropical humid seasons is only significant to a depth of 0.5 m from the stack surfaces.
2. Basic moisture diffusion theory was very effective in predicting mc changes in a stack of wheat in a simulated tropical climate within a laboratory. It was almost as effective in warehouse conditions in the tropics.
3. In a savannah climate, substantial increases in mc occurred on the outside of the stack during the humid season. Although these did not bring the grain to an unsafe mc, there would be considerable variation in mc between different sacks of millet if grain were dispatched from store during that season.
4. In a hot humid climate, moisture increases on the outside of the stack brought the rice to a mc approaching that at which mould growth could occur.

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Figure 1

The vertical plane through the stack of bags of wheat containing sensor holder C. The approximate positions of the pairs of Reethorpe and thermocouple sensors (•) on the holder are shown. The other two holders (A and B) and their sensors are not shown. Additional thermocouples (not shown) were located in the stack interior

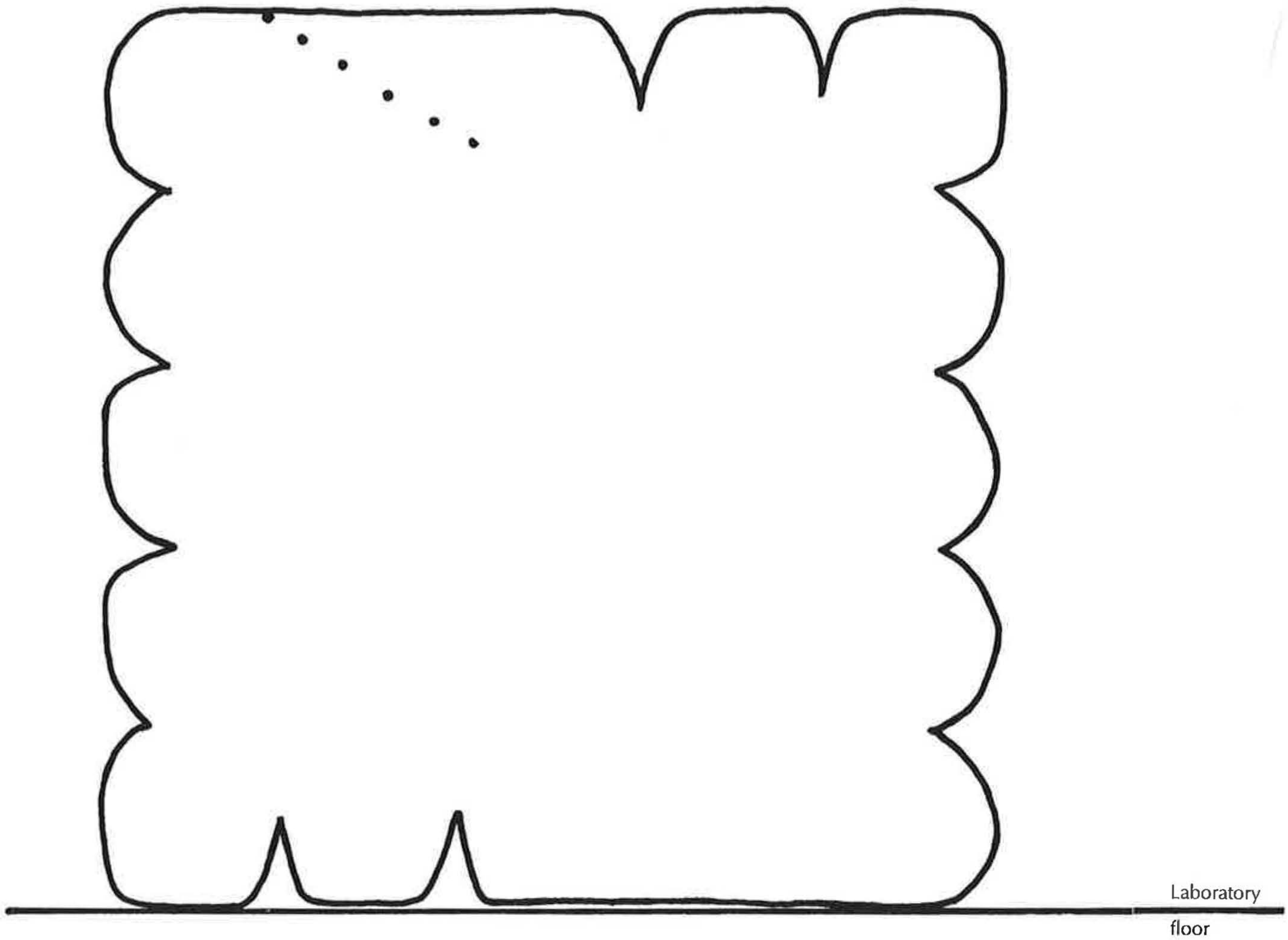


Figure 2

Maximum and minimum ambient air temperatures (°C) compared to the temperatures (°C) at the centre of the bagstack during the savannah climate trial

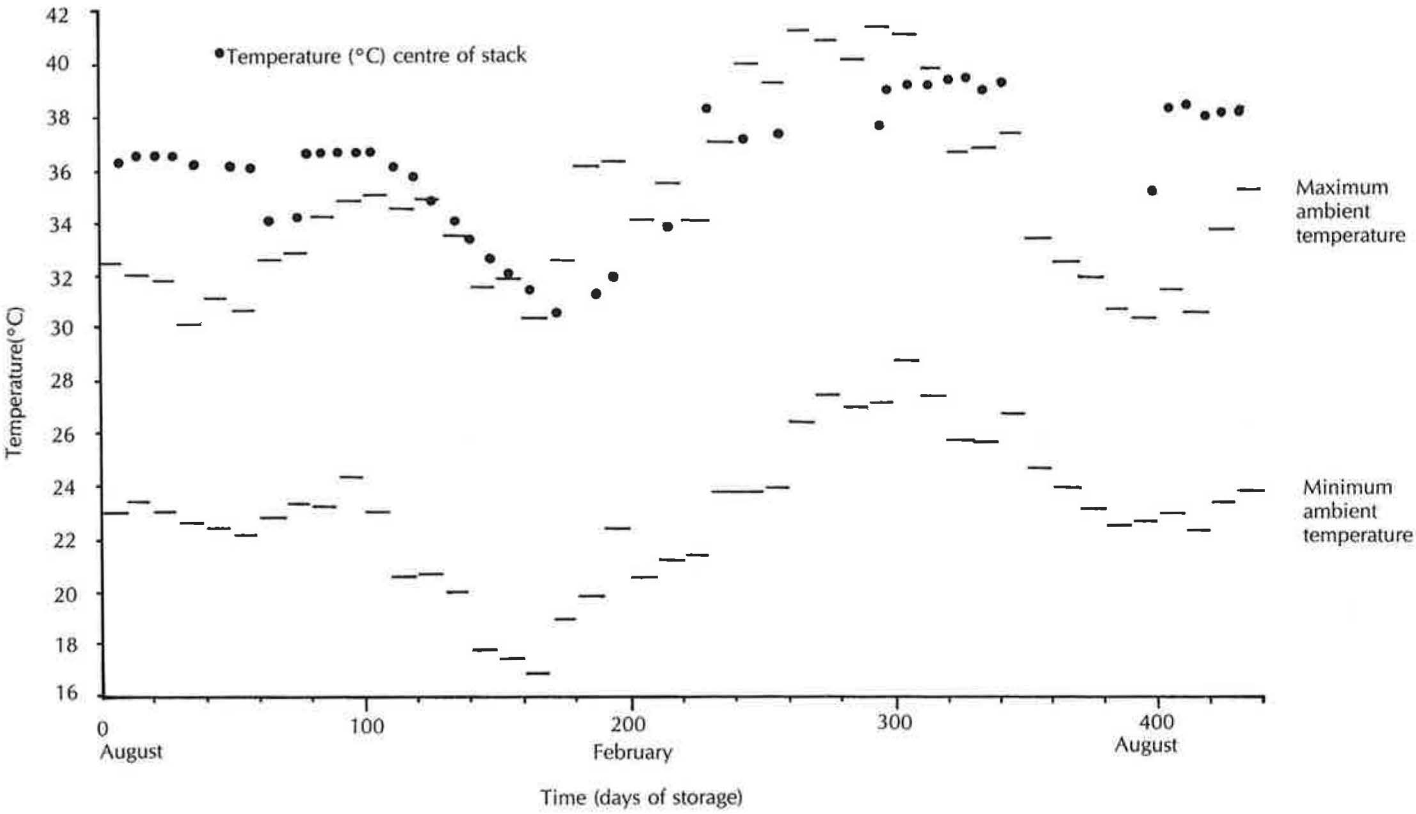


Figure 3

Average monthly ambient relative humidity during the savannah climate trial (●) and the corresponding values averaged over the previous 8 years (○)

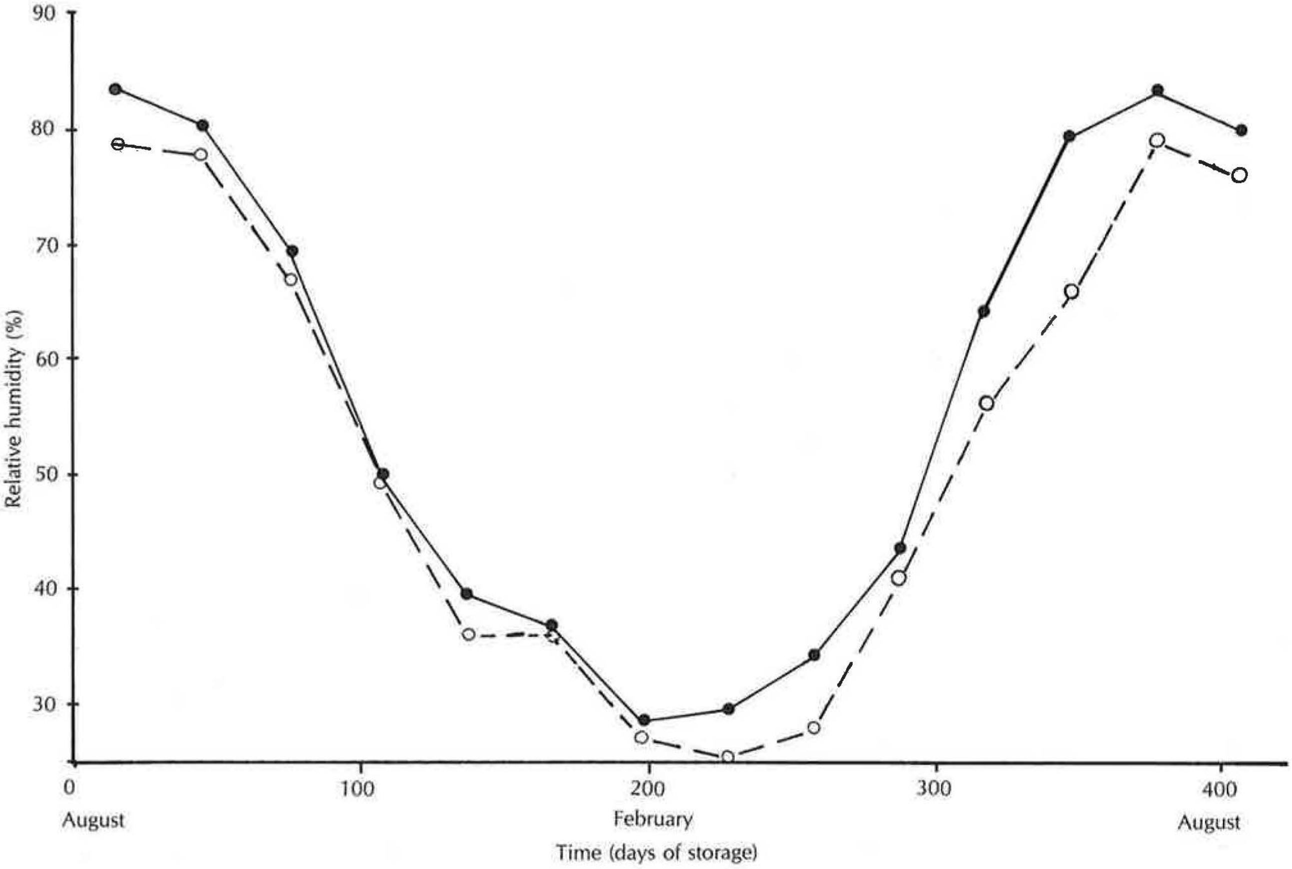
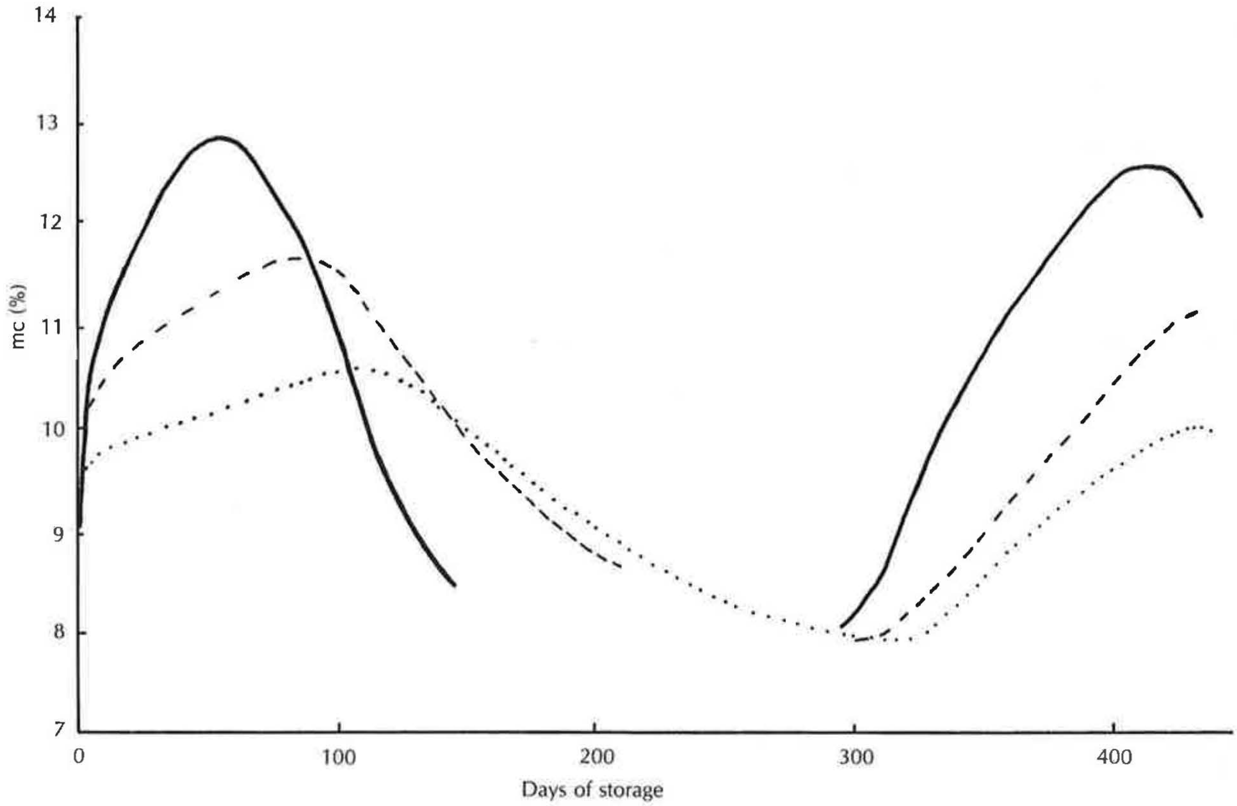


Figure 4

Observed mc values during the first field trial at three distances from the bagstack surface – 50, 150 and 220 mm indicated as ____, _ _ _, and . . . . . . respectively*



*Note that the monitors could not make mc measurements below 8% mc wet basis

Figure 5

Average monthly ambient temperature during the humid climate trial (o) and the corresponding values averaged over the previous 8 years (x)

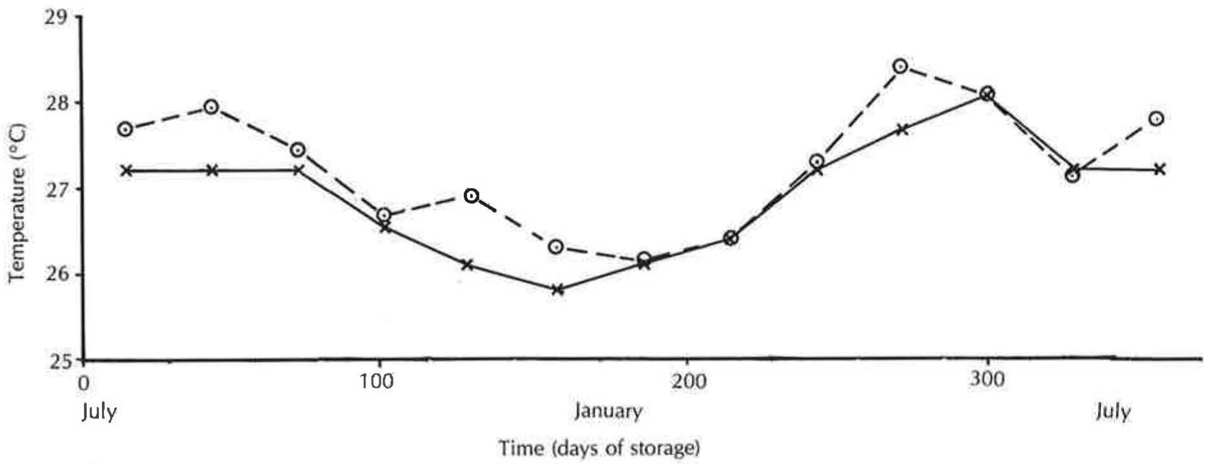


Figure 6

Average monthly ambient relative humidity during the humid climate trial (o) and the corresponding long-term averages (x)

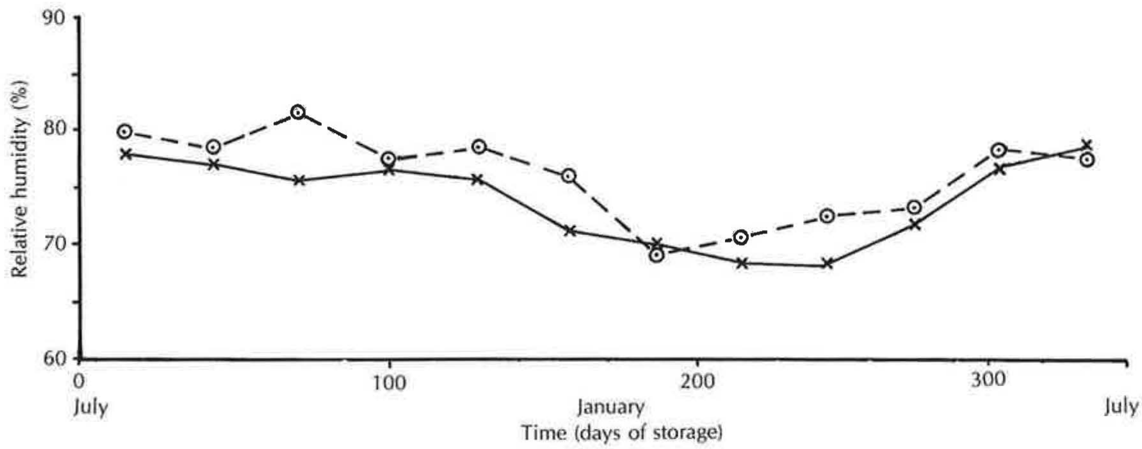


Figure 7

Mc changes at several depths into the bagstack during the humid climate trial

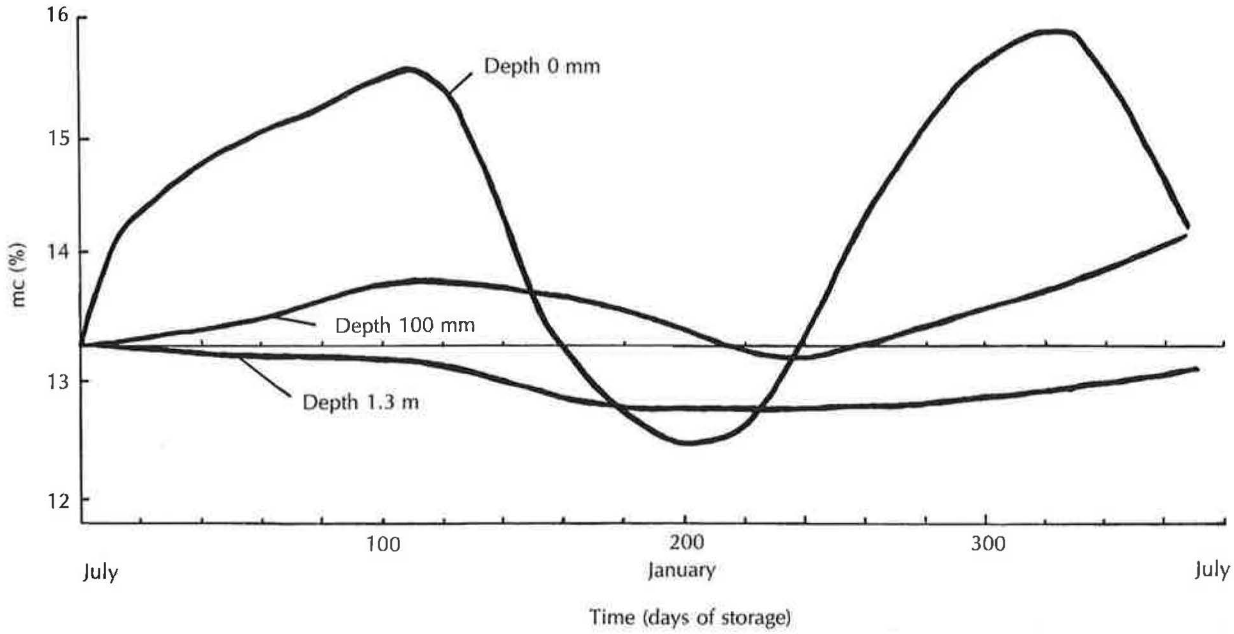


Figure 8

Measured mc values (X) from six Reethorpes on a Perspex holder in the bagstack on the 121st day of storage. The data predicted by equation (1) (*see* text) is illustrated by a line (————)

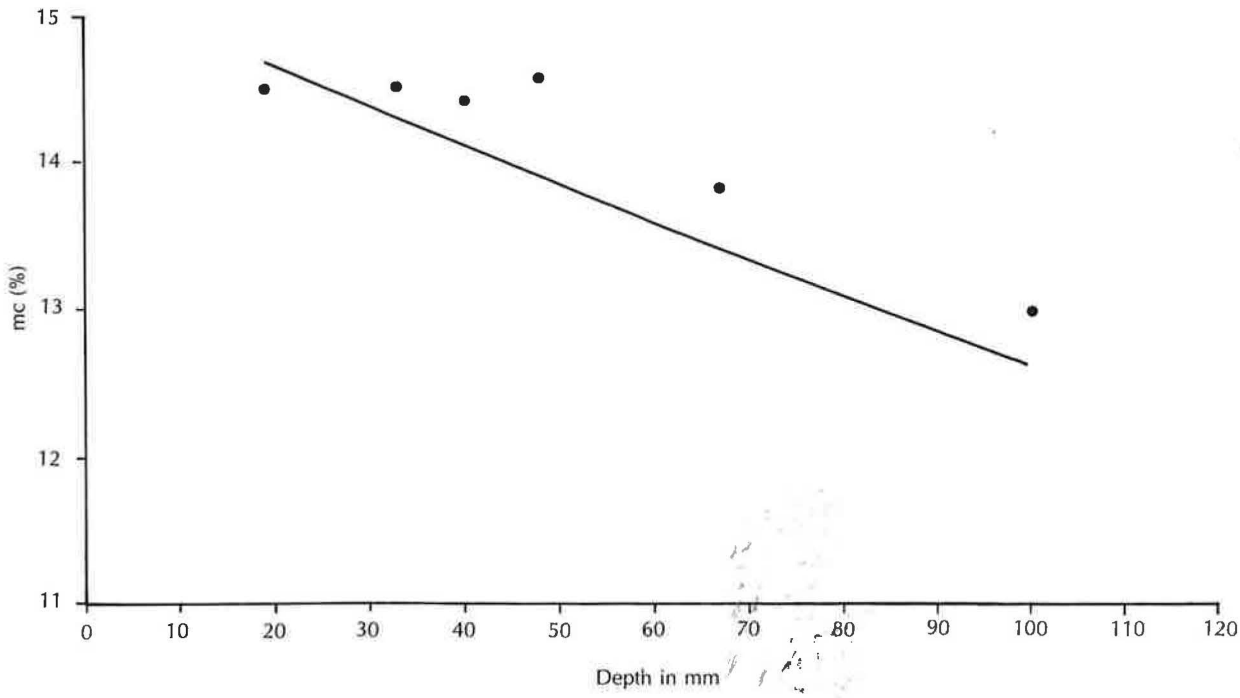


Figure 9

Laboratory trial. Differences between observed and corresponding predicted mc values for a range of depths from the stack surfaces during the fourth month of storage. The observed data is from 17 of the 18 Reethorpes on three Perspex holders (*see* text). The heavy line is the linear regression line for the difference data shown

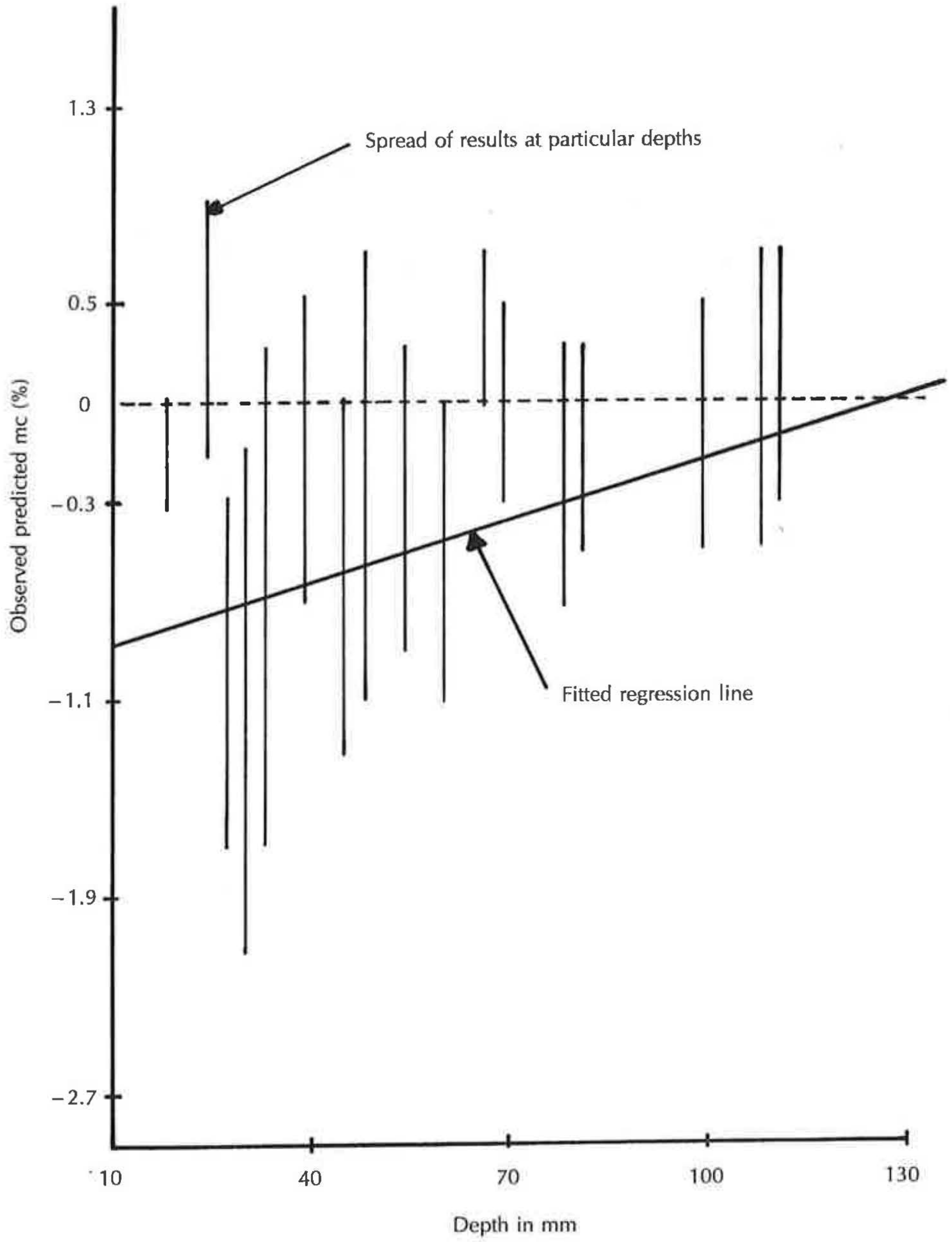
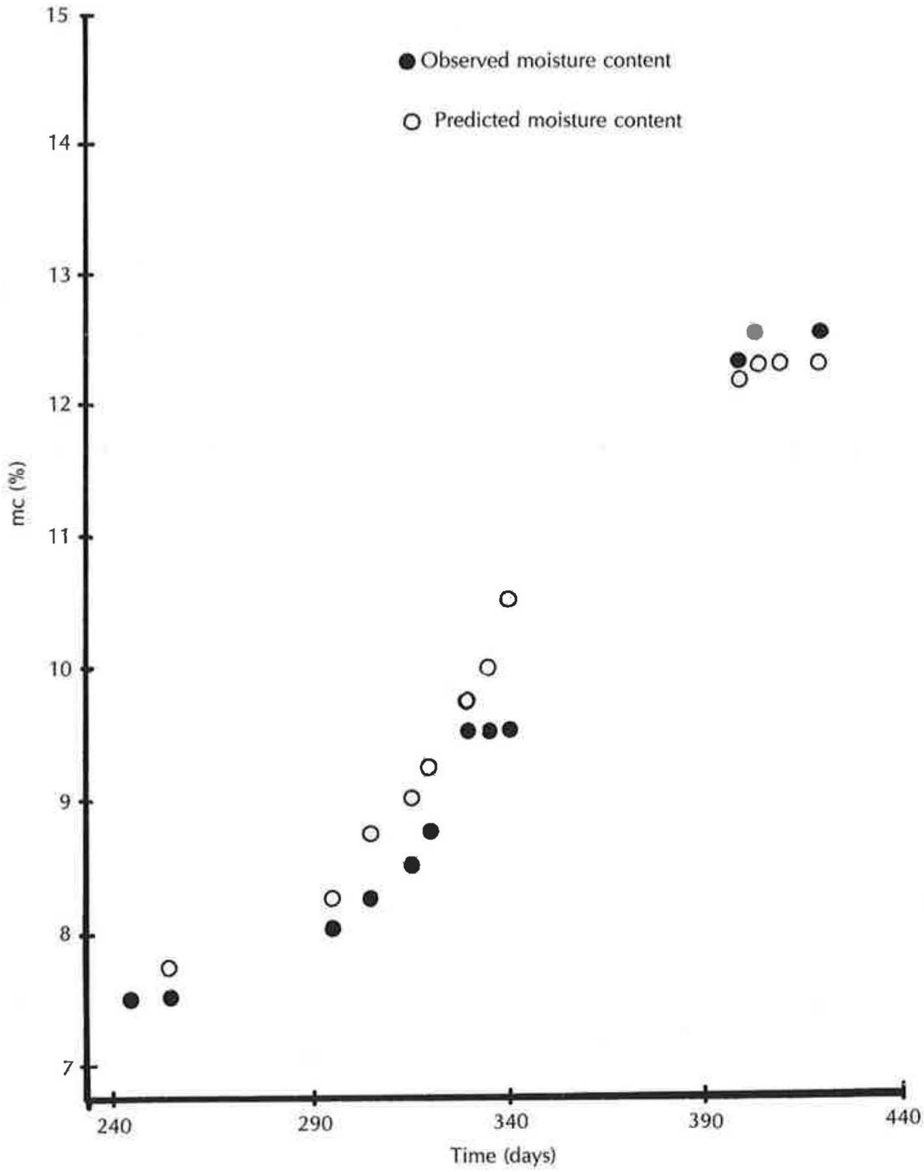


Figure 10

Savannah climate trial. Observed and predicted mc values from a typical Reethorpe 50 mm deep in the stack of millet during the second humid season



Figures 11 a – d

Savannah climate trial. Observed mc variations with depth from the stack surface from the beginning of the trial (a) through to the onset of the second wet season (d)

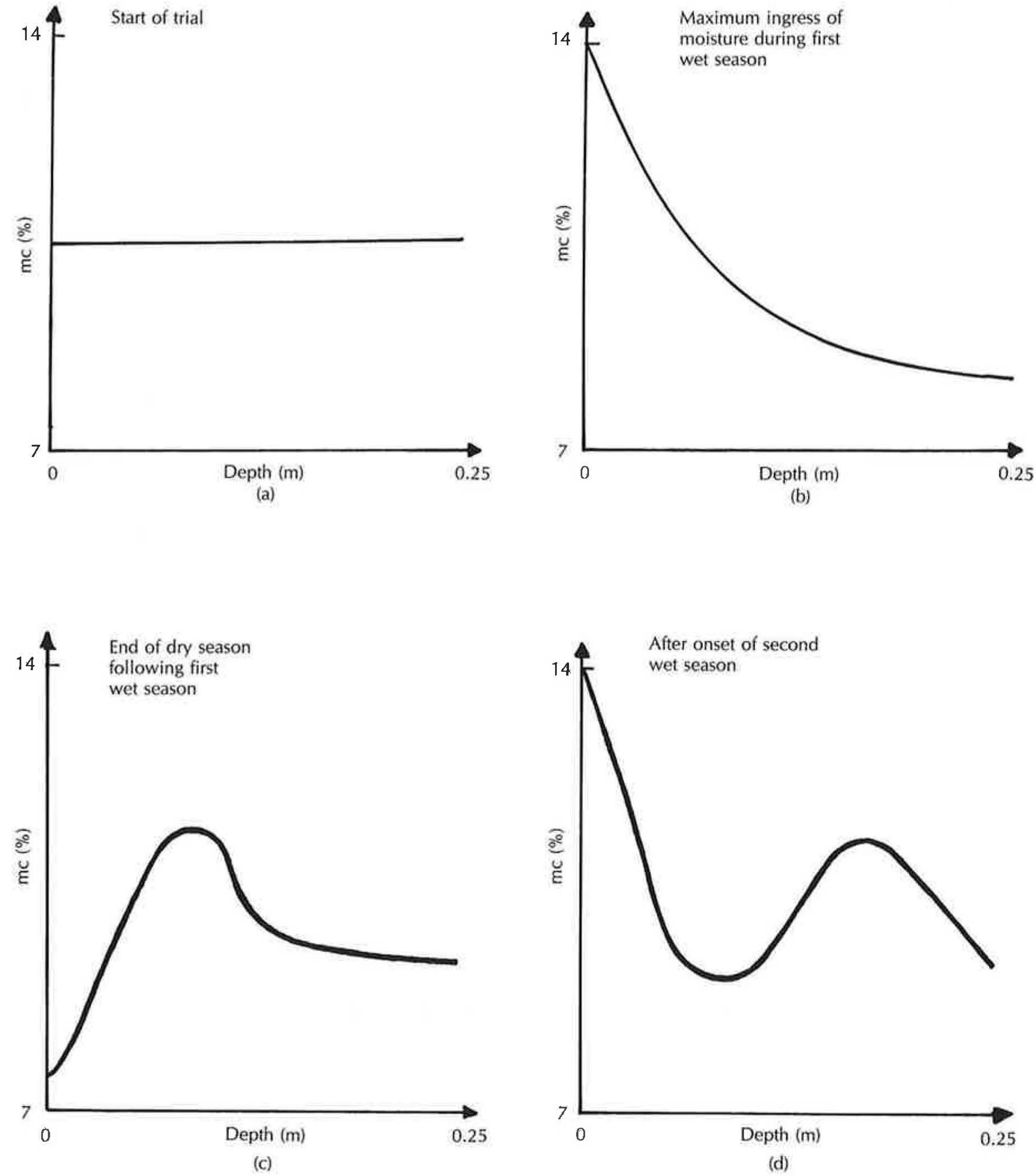


Figure 12

Savannah climate trial. Maximum increases in mc plotted against distance from the nearest stack surface during the first (●) and second (○) humid seasons. The lines show the predicted maximum values during the first (------) and second (__________) humid season

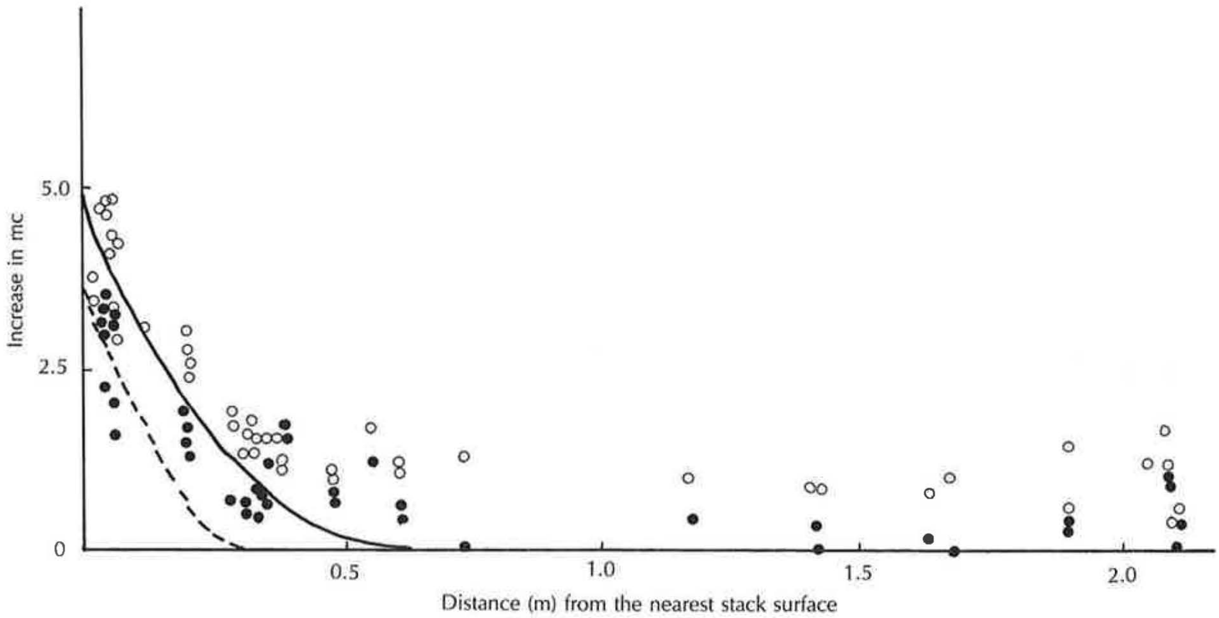


Figure 13

Observed (o) and predicted (●) mc changes plotted against time at a depth of 70 mm below the bagstack surface during the humid climate trial

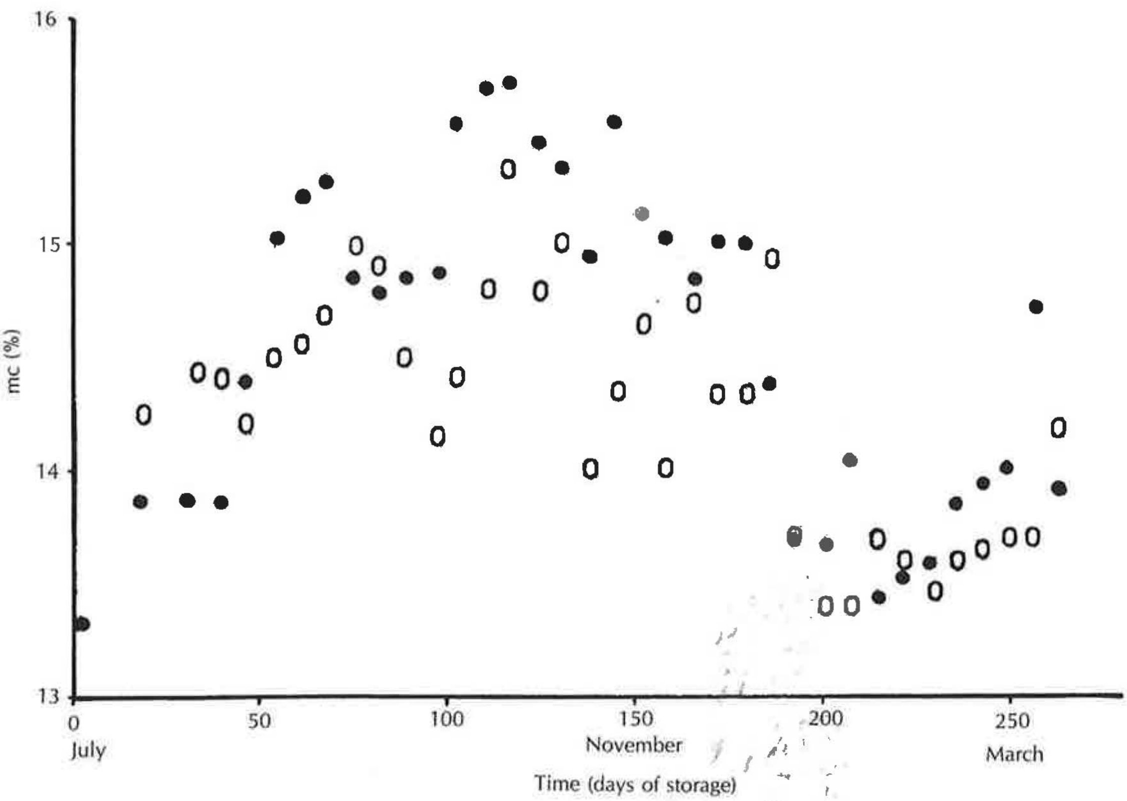
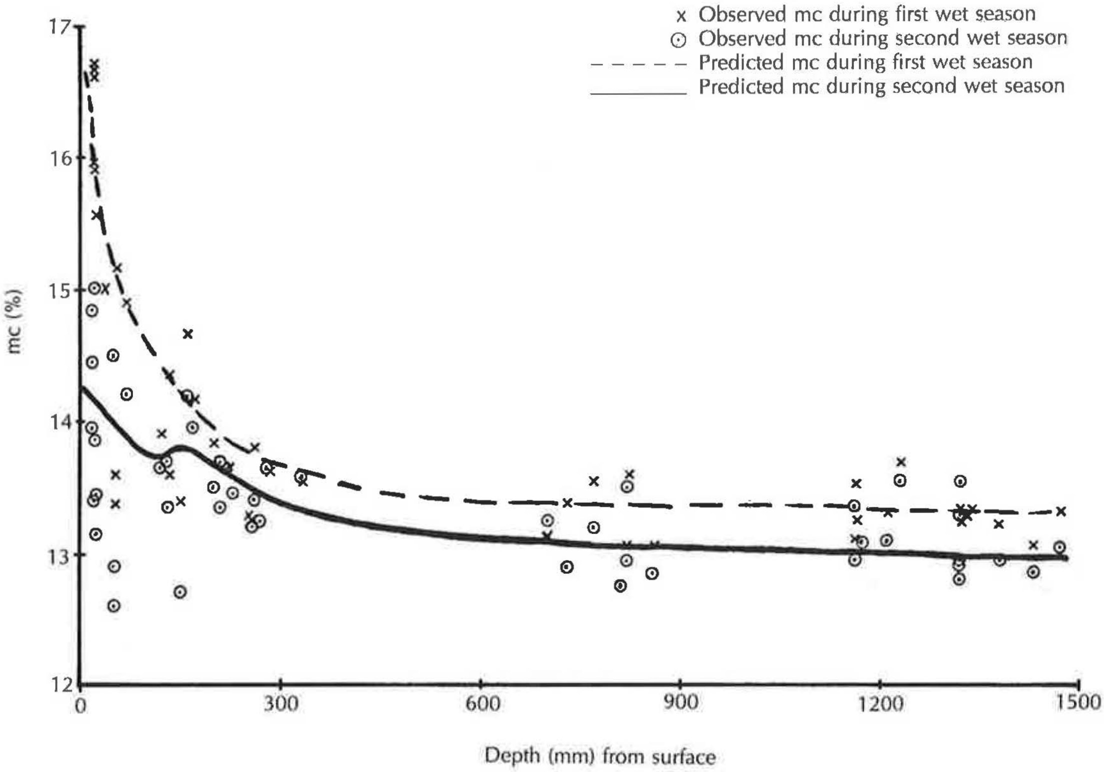


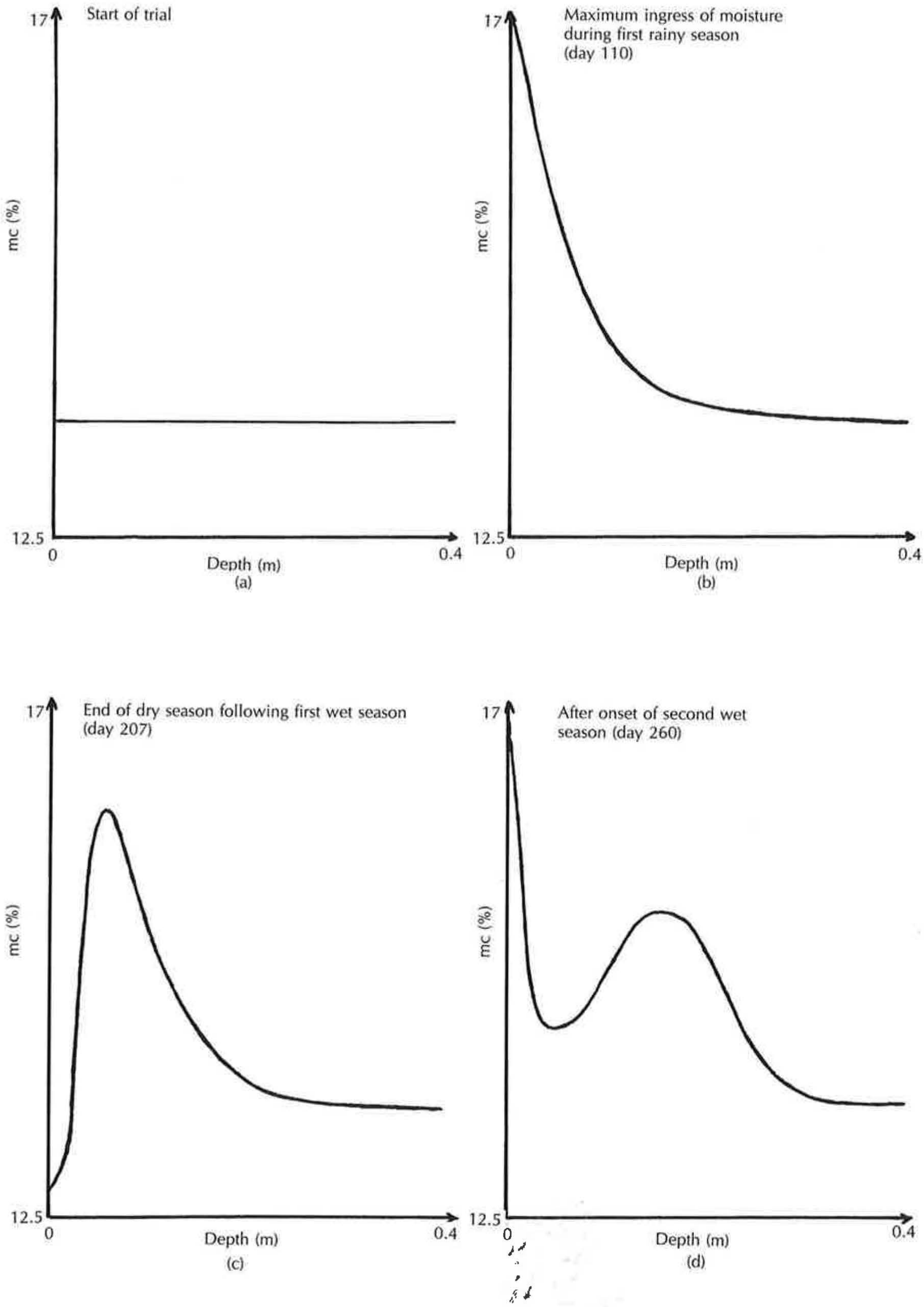
Figure 14

mc plotted against depth from the surface of the bagstack during the humid climate trial



Figures 15a – 15d

Observed mc variations with depth from the bagstack surface at various times during the humid climate trial



(140/89) Hobbs the Printers of Southampton