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Effect of physical factors, seed variety and quality on establishment of sorghum and cowpea.

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FINAL TECHNICAL REPORT ON:

Effect of physical factors, seed variety and quality on establishment of sorghum and cowpea

NRSP PROJECT No.: EMC XO213 **DATE:** 19/1/96

Executive Summary

Poor and failed crop establishment are commonplace in the semi-arid tropics (SAT) where they are major factors limiting crop yields for small farmers. Delayed or failed emergence can be caused by soil dryness and/or restriction to rooting, hardening of the soil above the shoot, sub or supraoptimal temperatures, too great or shallow a sowing depth, and combinations of these factors. Failure also occurs after emergence if root growth cannot keep pace with the drying front. Plants that emerge late also generally grow more slowly.

Guidance on the envelope of conditions (of antecedent rainfall, soil type, seed quality, sowing depths, cultivations) outside which there is a high risk of poor establishment or failure can help farmers to optimise their sowing practices. For example, when sowing into a drying soil, the safe range of sowing depths decreases and the importance of good sowing technique increases with time. Thus farmers not only need to know for how long after a given amount of rainfall it is safe to continue to sow, but also how to optimise their sowing practice in order to maximise quick emergence of late-sown seed.

A model of crop **establishment (GEM)** is being developed to address these problems. This project forms the first of a set of three linked projects that aim to produce, document, disseminate and provide practical examples of the use of GEM to support farmers in the SAT. The second phase (EMC XO237) will produce a computer model of crop **emergence** using the crop modelling parameters derived in this project (by August 1996). The third phase will concentrate on: what happens after emergence, validation, and documentation of a trial exemplar of dissemination of model predictions to farmers. A decision on this is pending. The model will also run using appropriate input parameters for other crops and varieties. Taken together, this work will reduce crop failure and poor establishment and hence increase overall crop yields in the SAT, since scarce sowing opportunities will be used more effectively .

In the first part of this first project, tests on a range of sorghum and cowpea seedlots available to farmers in Tanzania and Botswana showed that the quality of some seedlots (e.g. with germination <70%) was a major factor contributing to probable failed or poor establishment. This highlighted the need for work on improved seed storage and testing. We also showed that there was scope for selecting crop varieties on the basis of properties likely to give good emergence (fast germination and early shoot and root growth).

R5166
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FINAL TECHNICAL REPORT ON:

Effect of physical factors, seed variety and quality on establishment of sorghum and cowpea

R5166/01

NRSP PROJECT No.: EMC XO213 **DATE:** 19/1/96

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In the main part of this project, we have produced the crop-specific information needed to model the emergence of sorghum (var.Tegemeo) in terms of the germination, shoot and root growth of a population of seeds and their responses to temperature, soil dryness, and soil hardness. In addition, we have shown how simplifying concepts such as hydrothermal time can be used to speed up and simplify the process of modelling and the work required to parametrise future crop varieties.

Background

Efficient capture and use of light, soil water and nutrients by crops requires good crop establishment (Monteith & Elston, 1983). However, poor and failed crop establishment are commonplace in the semi-arid tropics (SAT) where they are major factors limiting crop yields for small farmers. For example, Harris (1992) found that, both in farmers fields and in researcher-managed trials, about 40% of sowings in Botswana failed. Mullins & Mtakwa (1995) found that Tanzanian farmers were acutely aware of the problems involved in obtaining good establishment but had to take risks because the time available with optimal sowing conditions was usually much less than that required to sow their land.

Delayed or failed emergence can be caused by soil dryness and/or restriction to rooting, hardening of the soil above the shoot, sub or supraoptimal temperatures, too great or shallow a sowing depth, and combinations of these factors (Townend *et al.*, 1995). Failure also occurs after emergence if root growth cannot keep pace with the drying front. In addition, plants that emerge late generally grow more slowly, and this is often associated with low yields (Austin, 1989, Carter *et al.*, 1992). With increase in the delay between germination and emergence, Durr & Boiffin (1995) found a progressive decrease in the relative growth rate (RGR) of sugar beet seedlings after emergence. Similar relationships are likely for other crops but need to be quantified.

Guidance on the envelope of conditions (of antecedent rainfall, soil type, seed quality, sowing depths, cultivations) outside which there is a high risk of poor establishment or failure can help farmers to optimise their sowing practices. For example, when sowing into a drying soil, the safe range of sowing depths decreases and the importance of good sowing technique increases with time. Thus farmers not only need to know for how long after a given amount of rainfall it is safe to continue to sow, but also how to optimise their sowing practice in order to maximise quick emergence of late-sown seed.

To address these problems, **GEM**, a model of crop **establishment** is being developed, in collaboration with Reading University and the Sokoine University of Agriculture in Tanzania. The model will also be useable as a front end to the ODA "PARCH" crop growth model to correct for differences between the sowing density and the actual density and quality of establishment. This project forms the first of a set of three linked projects that aim to produce, document, disseminate and provide practical examples of the use of GEM to support farmers in the SAT. Demand for the project was identified through discussions with NRI, D. Harris, who worked on the ODA Dryland Farming Project in Botswana, and with collaborators on previous projects in the SAT (specifically, staff at the Sokoine University of Agriculture, Tanzania.

The first part of the project was also included after discussions with NRI, in order to provide background information on the likely limitations caused by poor seed quality (low vigour) in the SAT, since it was clear that seed quality and crop establishment interact.

Project Purpose

The project has the following stated objectives:

i) To determine the range of quality (vigour) of available planting material (sorghum and cowpea) in the SAT.
ii) To identify the effect of seed variety and quality on germination and on initial root and shoot growth under optimal conditions.
iii) To examine the interactions between seed quality, crop variety and soil physical conditions (temperature, matric potential and mechanical impedance).

The first two of these objectives aim to discover the extent to which the quality of seed available to farmers (commercially and from state seed farms) is likely to affect emergence. They also aim to show the variability in germination and growth parameters between different varieties that might be used in selecting varieties suitable for optimal emergence under limiting conditions.

Part (iii) is the main focus of this project, with the aim of producing a complete set of parameters that are needed to model the emergence of sorghum (var.Tegemeo). These cover the germination, shoot and root growth of a population of seeds and their responses to temperature, soil dryness (matric potential), and soil hardness (penetration resistance), including the likely interactions between these factors.

These results feed into a model of crop **emergence** (EMC XO237) and are ultimately planned to be used in **GEM**, a model of crop **establishment** that will be disseminated and used to:

a) Produce a range of sample sowing scenarios for any given area that will demonstrate to farmers the effect of factors such as: soil type and cultivation depth, sowing depth, and the amount of antecedent rainfall on the percentage emergence, survival and vigour of seedlings. This will be used by local advisers to develop and improve local sowing practice.
b) Identify the major factor or factors responsible for poor crop establishment in a given area.
c) Test the potential of novel techniques such as seed soaking and mulching to improve establishment in a range of sowing scenarios.
d) Determine the sensitivity of crop establishment to seed properties such as thermal time to germination, shoot growth response to temperature etc. in a range of sowing scenarios as a guide to breeders on the most useful crop parameters for improving emergence in a given climate.

e) Act as a front end to the ODA-PARCH crop growth model, to allow it to produce realistic predictions of crop yields and determine the relative importance of establishment, and post establishment growth as components of yield.

Research Activities

1. Range of quality of planting material available

Thirteen different seed lots of sorghum and seven different seed lots of cowpea from Botswana and Tanzania were provided by Mr.D Jackson (NRI). Seedlots were inspected under a binocular microscope and the extent and type of damage recorded. Germination was tested at 20^0C by the standard germination test and by extrapolation from a series of controlled deterioration tests (as K_i) (Matthews, 1980). Germination of cowpea on wet seed papers on a Petrie dish was unreliable due to the prevalence of fungal attack. The better results reported here were obtained from rolled paper towels.

2. Effect of seed variety and quality on germination initial root and shoot growth under optimal conditions

Time to 50% germination (t_{50}) values were determined on all seed lots after excluding damaged seed. More detailed studies were also performed on some seedlots to determine the specta of germination times.

The effects of temperature on germination percentage and rate of germination ($1/t_{50}$) were studied for four varieties of sorghum and cowpea using a temperature gradient plate (Dunbabin et al., 1994).

Root and shoot growth - modification of the original proposals

In tests using the standard wet paper towel technique to study root and shoot growth. Sorghum roots grew at about one third of their optimal rate (as determined in moist expanded vermiculite). This means that the standard technique is unacceptable for sorghum (probably because there is inadequate oxygen supply to the seedling). We have also found that there is a significant effect of light (even green safe light) on sorghum mesocotyl and coleoptile extension rates so that these cannot be regularly monitored but can only be determined by sequential destructive sampling (Dunbabin et al., 1995). Further tests with sorghum have shown that root and shoot growth are slightly faster in moist sieved (1-3.35 mm) natural soil aggregates than in moist expanded vermiculite or loose-packed sand. For these reasons and to facilitate control of matric potential and penetration resistance, we have therefore standardise on the use of this soil for all work on root and shoot growth. Because of the greatly increased experimental work required to measure root and shoot growth rates using destructive sampling, the experimental programme was rescheduled, with NRI agreement, to concentrate solely on a single sorghum variety, Tegemeo.

3. Parametrising time to germination as a function of temperature and matric potential

Time to germination as a function of temperature and matric potential was studied by germinating seed batches in phytotrons set at four different temperatures on filter-papers permanently moistened by a wick dipping into polyethylene glycol (PEG) solutions at five different matric potential. Experimental methods and data analysis have been described by Gummerson (1985). In addition the PEG solutions were calibrated using a Richards psychrometer to improve accuracy.

4. Measuring shoot and root growth as a function of temperature, matric potential and mechanical impedance

Sorghum shoot and root growth of unemerged seedlings were found to vary with time after germination as shown in Fig. 4. We aimed to model the initial (linear) portion of root growth and the shoot growth up to the point where no further growth occurs. Consequently, destructive measurements of root and shoot (coleoptile and mesocotyl) length with 4 or more replicates were obtained at four times after germination for 35 combinations of temperature and matric potential. Temperature was maintained constant by performing the experiment in phytotrons and monitored with a datalogger to ensure accuracy. Matric potential was controlled by moistening the sieved natural aggregates to moisture contents calculated to give the required values (from a previously obtained moisture release characterisitic), and was checked using the filter-paper technique (Deka et al., 1995) before and after several of the runs to confirm that there was a limited change during the experiment.

Most experiments were performed with the soil packed to a dry bulk density of 0.88 Mg m^{-3} which gave a very low penetration resistance (<0.25 MPa) insufficient to reduce growth rates, but a separate set of experiments was run at 1.25 Mg m^{-3} (PR = ca.1 MPa) to determine the effects of mechanical impedance.

Outputs

1. Range of quality of planting material available

(A more detailed version of this section was included in the first annual report (1993))

Sorghum

For all but one seed lot (Serena), the main source of damage was due to insects (seed boring weevils) amounting to up to 19% of the seed lot. Damaged seeds were excluded from the seed lots for further experimental work. Tests of germination and of Ki (the germination % obtained by extrapolating the results from controlled deterioration tests) gave a similar but not identical rank ordering of seed vigour. Germination varied from 56 to 95 %. Taking the following as an approximate set of criteria for Ki or germination %, the thirteen seed lots were classified as:

	No. of seed lots
High vigour (Ki or germination ≥ 95%)	4
Acceptable vigour (Ki or germination ≥ 90%)	4
Tolerable vigour? (Ki or germination ≥ 80%)	4
Unacceptable (Ki or germination < 80%)	1

These results highlight the limited quality of available planting material and the importance of seed quality. Combining the effects of seed damage and germination %, it is worth noting that, **under optimal conditions**, only two seed lots (Mbagala (1) & Town) would have given >90% germination and two would only have given 54 % germination.

Cowpea

Both insect damage (ranging from 2 to 14%) and cracked seeds (ranging from 2 to 13%) were found, with a maximum of 20% of damaged seeds in one lot. Cracked seeds result in imbibition damage leading to failed emergence. Damaged seeds were excluded from the seed lots for further experimental work. Both estimates of germination (germination % and Ki) ranked seeds in a similar fashion. Using the same set of criteria as for sorghum, the seven seed lots were classified as follows:

	No. of seed lots
High vigour (Ki or germination ≥ 95%)	4
Acceptable vigour (Ki or germination ≥ 90%)	0
Tolerable vigour? (Ki or germination ≥ 80%)	1
Unacceptable (Ki or germination < 80%)	2

Combining the effects of seed damage and germination %, it is worth noting that, **under optimal conditions**, only two seed lots (Vuli (2) and Tswana) would have given >90% germination and two would have given <65 % germination. As with sorghum, the quality of some of the planting material may be a major factor leading to poor or failed emergence.

2. Effect of seed variety and quality on germination initial root and shoot growth under optimal conditions

Time to 50% germination (t_{50})

Sorghum

t_{50} values for the 13 sorghum seed lots at 20^{0}C varied from 35 to 54 h. Other work in the Department has shown that time to germination increases with ageing (i.e. with reduction in vigour). Results for two paired seed lots, Tegemeo and Mbangala also demonstrate this with the lower vigour seed lots having a longer t_{50}, although in only one case was the effect significant.

Cowpea

t_{50} values varied from <24 to 40 h. As with sorghum, the lower vigour seed lot of Vuli seed had a longer t_{50}.

Spectra of germination times

The spectra of germination times for three of the sorghum varieties that had similar values of t_{50} are show in Fig.1. These results illustrate the importance of this kind of information for modelling. Suppose for example that seeds which had not germinated after 44 h would fail to emerge because of surface hardening. About 50% of varieties. Tegemeo 1 and Segolane would have emerged under this scenario whereas only about 26% of var. 65D would have emerged.

Source of variation in germination times

For the two Tegemeo seed lots studied, t_{50} increased significantly ($P \leq 0.05$) as seed size decreased. The two seed lots also differed in their seed size distribution. Thus, for any given seedlot, the spectrum of germination times depends not only on seed quality, but also on the distribution of seed sizes, which may vary from one lot to the next. Furthermore the variation in germination times within any seed lot is at least in part due to the range of seed sizes present. These results are in line with other published for cereals, but are important here because they indicate that there is a limit to the extent to which the distribution of times to germination for a given variety, obtained on one seedlot can be taken to represent another seedlot of the same variety, even if both seedlots are of high vigour. We have avoided this problem in our model validation by using subsamples from the same seedlot for parametrising the model and for field experiments in Tanzania.

Variation of germination with temperature

Examples of the variation of rate of germination ($1/t_{50}$) and percentage germination with temperature are shown in Fig. 2. Similar curves were obtained for all four sorghum varieties studied (65D, Tegemeo, Segolane, and ICSV-112). All varieties had a base temperature of 9^{o}C (except ICSV-112, 10^{o}C), optimum temperature of 38^{o}C and maximum temperature 43^{o}C and thermal time to germination of 23-24 ^{o}Cd except 65D (28^{o}Cd). More detailed results are published in Dunbabin et al., 1994.

For cowpea, the rate of germination reached a plateau between 30 and 38^{o}C. This means that modelling cowpea germination will require a different type of function to that for sorghum.

Initial shoot and root growth

Figure 3 shows that, under optimal conditions, aged (i.e. low vigour) and high vigour seeds did not have significantly different root and shoot growth rates. However the aged seeds did take longer to germinate. Results in this figure (especially the comparison between varieties) should be treated with caution because they were not obtained in sieved soil aggregates and the results for Tegemeo are much less than was obtained in our later and more detailed work.

Modelling germination rate of sorghum (var. Tegemeo) as a function of temperature and matric potential

(This work was analysed with assistance of collaborators in EMC XO237)

The temperature gradient plate has also been used to check that the concept of thermal time used for modelling is applicable to seeds germinating under a fluctuating temperature regime. Our results show that, providing the upper temperature is <40^{o}C the concept of thermal time is still applicable (the lowest temperature tested was 14^{o}C).

For modelling, thermal time accumulated after a unit of time at temperature T, is calculated by adding on R units of thermal time to the accumulated total.

If $T < To$, then $R = T - Tb$

If $T > To$, then $R = To - Tb - (T - To) (To - Tb / Tm - To)$

where Tb, To, Tm, and T are the base, optimum, maximum, and actual seed temperatures, respectively.

Using a large set of thermal table data, thermal time was plotted against the proportion of germinated seeds, p and it was found that accumulating thermal time at 25°C all the time or alternating 15°C and 35°C made little difference, and that all points could be fitted to roughly the same Gompertz function:

$$\theta_p = (21.6017 - (\ln(\ln p))/0.15760)*24$$

where θ_p is the thermal time required for the last of a proportion p of the seeds to germinate.

By germinating seeds on filter-paper moistened with polyethylene glycol mixed to give a range of osmotic potentials it was found that the rate of germination decreased linearly with matric potential, that this behaviour was repeatable at a range of temperatures, and that a single equation could be used to describe the combined effects of temperature and matric potential on the so-called hydrothermal time to germination (Gummerson, 1985):

$$\theta_{p,\psi} = (A - B \ln(\ln p))/(1 + C\psi)$$

where A = 16.521 °Ch, B =116.468 °Ch, C = 0.000625 kPa^{-1}, ψ is matric potential in kPa, and $\theta_{p,\psi}$ is the thermal time required for a proportion p of seeds to germinate at a matric potential ψ.

Although PEG is very useful for establishing the hydrothermal time relationship (because seeds can be readily inspected during germination), we find that seeds germinate approximately 1.3 times faster in our aggregated soil at any given potential, probably due to the greater proportion of the seed surface in contact with water. We have therefore reduced the thermal time to germination to compensate for this in fitting the above parameters and checked our predictions against results obtained with soil.
(This work is only just completed and full details will be given in the report on EMC XO237).

4. Measuring and modelling shoot and root growth as a function of temperature, matric potential and mechanical impedance

(This work was analysed with assistance of collaborators in EMC XO237)
Typical results for the variation of sorghum shoot and root growth with time (Fig. 4) indicate that shoot growth can be modelled by a lag time t_a followed by a constant growth rate r_s, and that (except for seeds deeper than ca. 100 mm) pre-emergence root growth rate can be modelled by a constant growth rate r_r. Curves of shoot growth versus time for the 35 temperature/matric potential combinations were therefore inspected and the linear growth phase was extrapolated to estimate t_a. It was found that $1/t_a$ was a linear function of temperature, T so that t_a could be expressed in terms of an additional thermal time θ_s required for shoot growth to start after emergence:

$$t_a = \theta_s/(T - T_{bs})$$

where, $T_{bs} = 5^oC$ and $\theta_s = 696.03\ ^oCh$

This function was then used to predict the intercept on the time axis at any temperature, and the growth curves were reinspected to draw the best linear growth functions through this intercept and hence obtain a set of values for r_s in terms of T and matric potential, ψ. Genstat was then used to give a least squares fit to the folowing function:

$$r_s = a\ \{\ b + (\ c - dT_s)\ g^{T_s}\ \}\ \{A + BC^{-\psi_s}\}$$

where: T_s and ψ_s are the temperature at the shoot meristem and at the root tip respectively, and a, b, c, d, g, A, B, and C are fitting constants given by:
0.5338, -1.245, 0.47313, 0.01101, 1.11881, -0.0119, 2.016, and 0.9990 respectively. The fitted function (Fig. 5) was within ± 0.5 mm h^{-1} of 35 of the 36 experimental estimates and demonstrates that the temperature and matric potential effects on shoot growth rate can be treated independently.

The same function was found to be suitable for modelling root growth rate except that there is no delay after germination (when initial root length is taken as 4 mm). The corresponding values for the fitting constants are:
0.6091, -2.0006, 1.24307, 0.02688, 1.07001, 0.219, 1.732, and 0.9990.
It is reasonable to assume that this will also apply to other sorghum varieties (and may well apply to other cereals) thus greatly reducing the experimental work required for parametrisation in future.

An experiment in which either roots or shoots or both had to grow in soil with a high penetration resistance showed that there was no significant interaction between shoot growth and the effects of impedance on root growth and vice versa (Fig. 6). Impedance had a greater effect on shoot than on root growth in agreement with published work for maize. Soil with a penetration resistance of 1 MPa reduced shoot growth rate by approximately 60%. A more extensive dataset obtained for sorghum, using the same growth medium, will be used for modelling, the effects of impedance on root growth rate.

5. Appraisal and site selection visits to Botswana and Tanzania

These visits really form part of the second project phase (EMC XO237) but had to be budgeted in this project to allow appraisal prior to approval of phase two. Dr. Simmonds and myself visited a number of sites in Botswana and Tanzania in March 1993 and selected two, with contrasting soil types to representing soil types to span a range of soil types common to the SAT. Sites were chosen for use for collaborative fieldwork with Dr. P. Mtakwa (Sokoine University of Agriculture, Tanzania) in phase two to provide field data with which to validate the model and provide representative model soil parameters. A detailed plan of work was also developed for each site (Mullins & Simmonds, 1993).

Achievement of project objectives

Subject to the agreed programme modification to concentrate on sorghum, the project objectives were met. Less work was done on seed quality than originally planned since detailed specification of the limitations posed by poor quality seed were not necessary once it was clear from experimental results and recent results by Prof. Naylor (from other research) that seed quality is indeed the probable explanation for poor or failed emergence of low vigour seeds. However, the work programmes on the use of hydrothermal time to describe germination and on shoot and root growth functions were more detailed than originally planned but in-line with the overall project aim. This work has provided a bonus by indicating the further simplifying assumptions that may in future be used in modelling sorghum and probably other cereals.

Contribution of Outputs

The ODA development goals relevant to this project are to increase the productivity of the Semi-Arid Production System. This will be increased both by reducing the risk of failed or poor crop establishment (resulting in a later, less favourable sowing opportunity having to be used to resow or gap-fill), and by improving the percentage and vigour of established plants. Given the current estimates on the limitations due to establishment in the SAT, the ability to maximise crop establishment must represent a major contribution to increasing yields, quite apart from spin-off benefits such as more efficient use of manures and fertiliser and reduced runoff risk.

a) What further market studies need to be done?

Although limited quantitative information is available on the extent and severity of crop establishment problems in the SAT, it is not clear that the cost of the surveys needed to substantially improve this information can be justified. Rather, the establishment model itself could be used, with past weather data and a limited amount of local verification and information on the distribution of sowing times, as a cost effective way to determine the limitations on overall crop yield due to poor establishment. What is probably more important is to discover and demonstrate the improvement in establishment that can be achieved with the help of GEM. Part of the purpose of the proposed third phase of this research is to address this aim.

b) How will outputs be made available to intended users?

The main output of the third phase of this project will be a computer model of crop establishment (GEM) and an accompanying manual which will be freely available on request. However, an important priority is that the model is able to sell itself. This means that publications and meetings will prove an important channel for advertising the availability of the model. In addition dissemination in Tanzania through our collaborator at the Sokoine University of Agriculture and the Department of Agriculture is incorporated into the proposal for phase three.

c) Further stages needed to develop, test and establish the model, and funding

The results from this project have already been used, as planned, to help develop and parametrise a model of crop **emergence** due to be produced by August 1996 and funded by ODA under the same programme (EMC XO237 "Modelling the seedbed physical environment in relation to crop emergence"). This work is planned to be taken forward into a third phase that will concentrate on: what happens after emergence, including the effect of delayed emergence on the relative growth rate of the emerged plants in order to produce **GEM**, a model of crop establishment that includes the emergence model. A fuding decision from ODA (NRSP) on phase three is currently pending.

Model validation (i.e. testing), based on two seasons of field data from two sites in Tanzania with contrasting soils, is already underway as part of EMC XO237, and sensitivity analysis is also planned. Phase three will involve further validation (of the establishment part of the model, and documentation of a trial exemplar of dissemination of model predictions to farmers in Tanzania.

Collaborative work with D. Harris to use the emergence model to allow wider application of results from research on "The development and testing of seed-priming to improve stand establishment, early growth and yield of crops in semi-arid Zimbabwe and India" (funded by ODA Plant Sciences) is already planned.

Once the usefulness and reliability of GEM has been established a future priority will be to broaden its application to a wide range of sorghum varieties and to other crops. For sorghum and crops that can be established to behave in a similar fashion (e.g. other cereals), we now know how to greatly reduce the work required to parametrise a seedlot. Further work required to test assumptions that could further reduce laboratory requirements may become a future priority, together with work on how to model other (e.g. epigeal) seed types. Once methods can be published on how to parametrise crops for establishment, it is then anticipated that the required work can and will be performed in a variety of locations by a variety of organisations (including CGIAR institutes, NAARS and Universities in the SAT).

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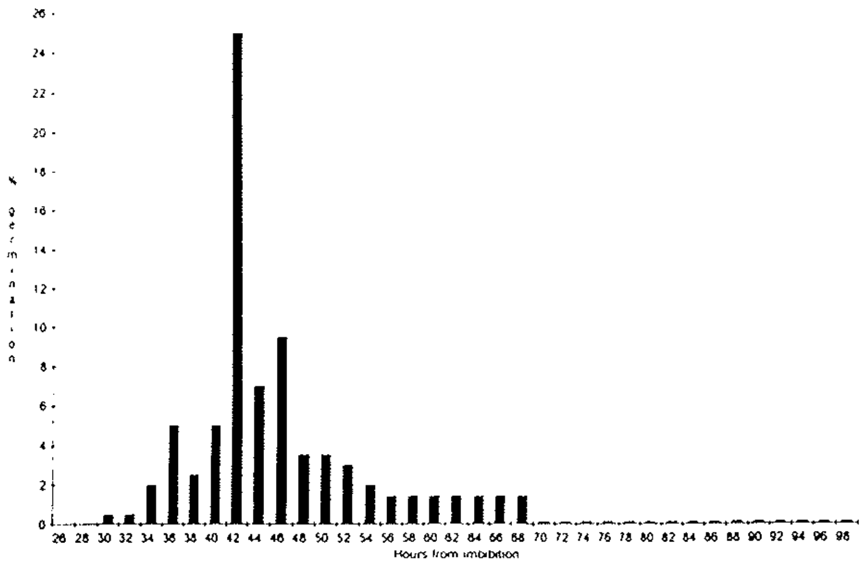
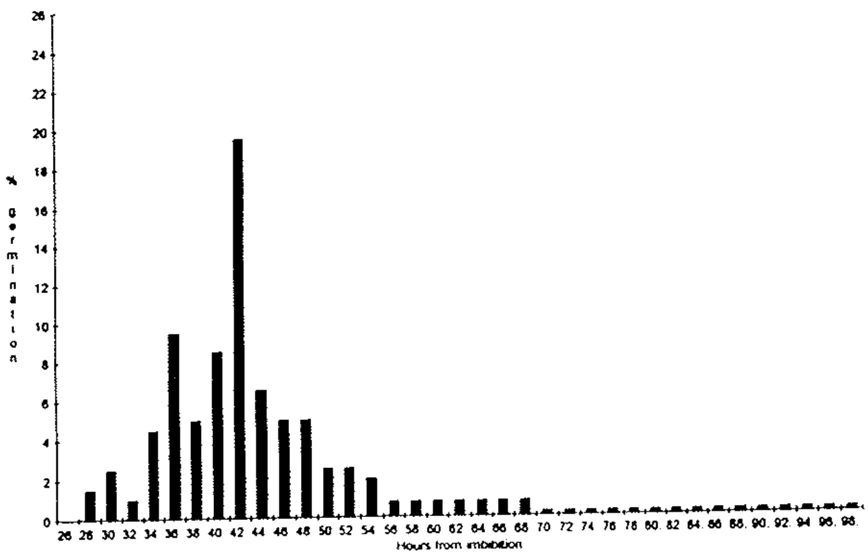
Fig 1 Distribution of germination times for 3 sorghum varieties

Sogolane - spread of germination FIG 2
@ 23°C



Tegameo 1 - spread of germination FIG 1
@ 23°C



65D - spread of germination FIG 3
@ 23°C

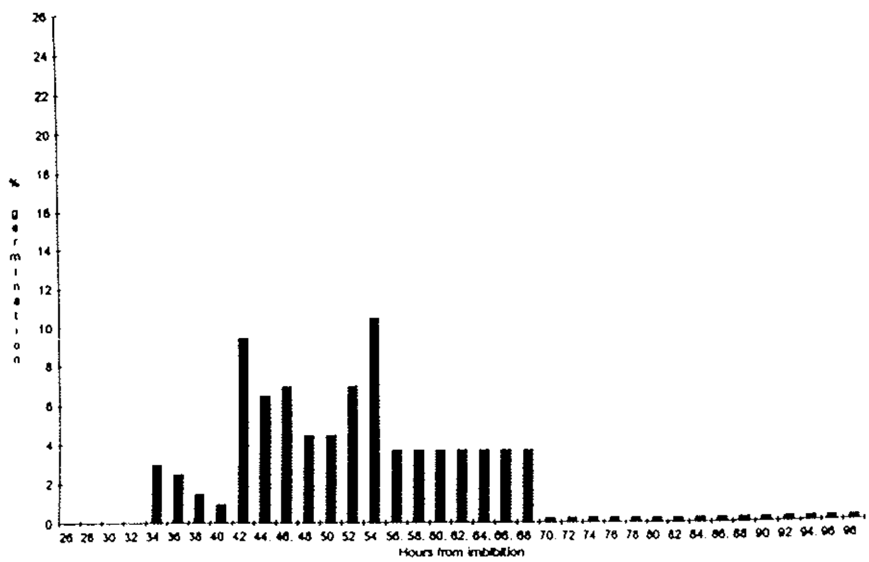
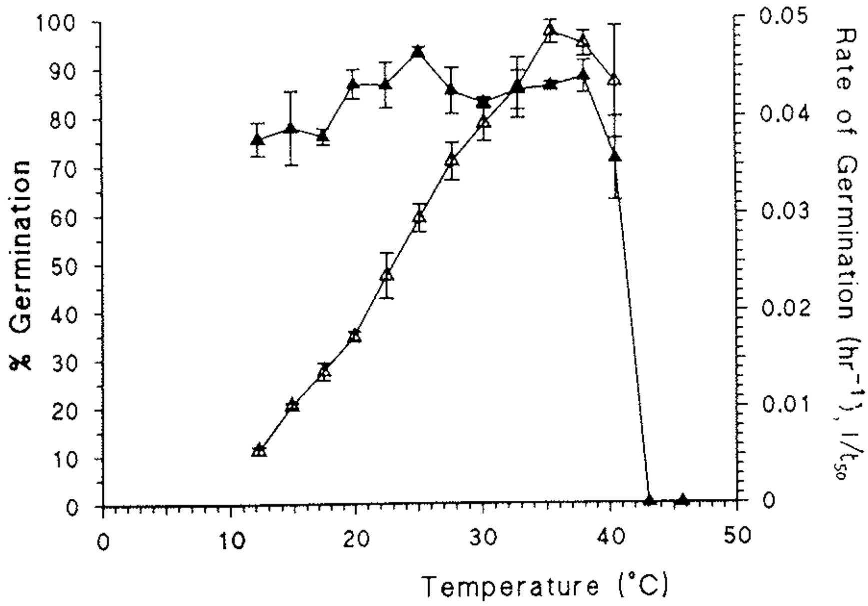
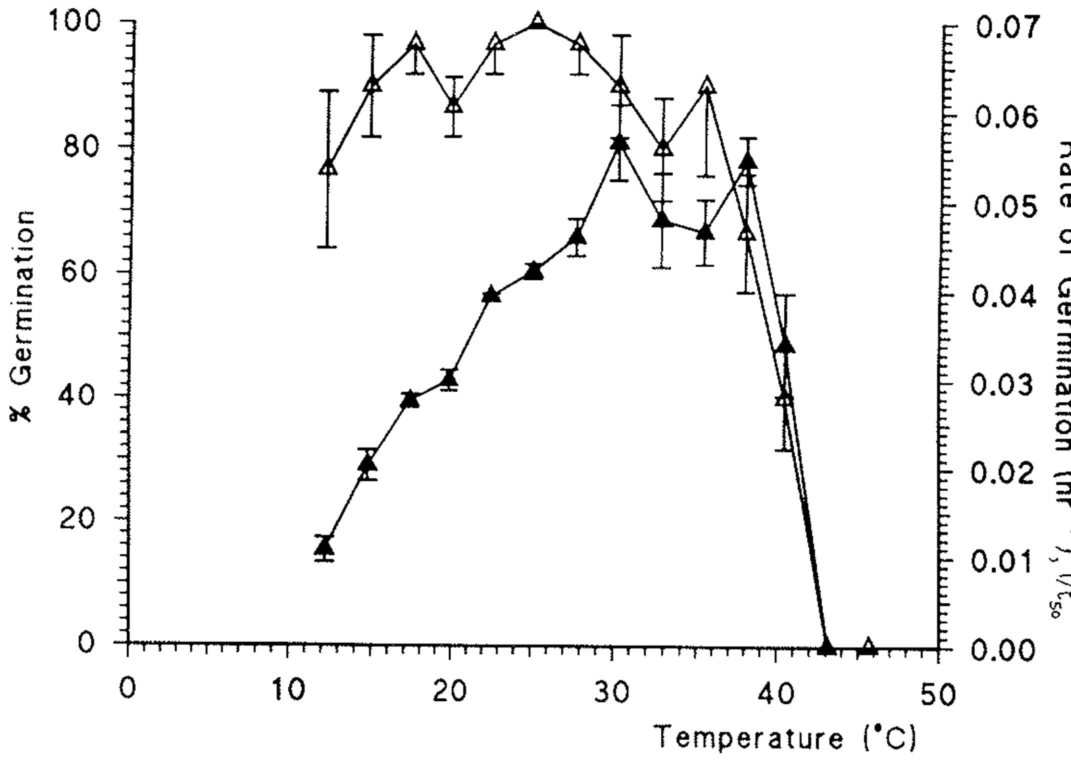


Fig 2

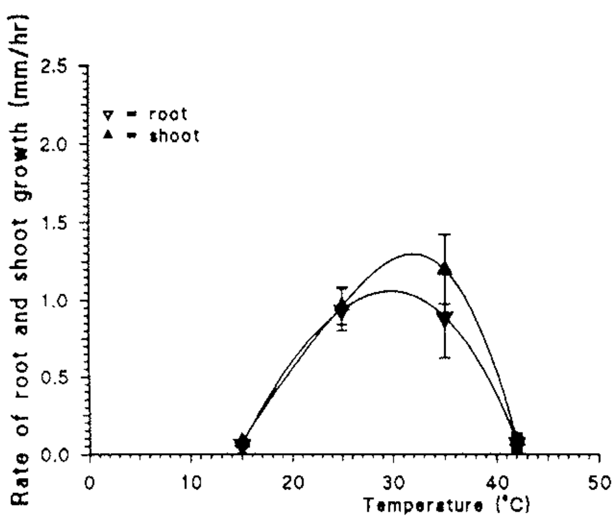


Sorghum cv. Tegemeo, % Germination (▲) and Rate of Germination (△) vs Temperature

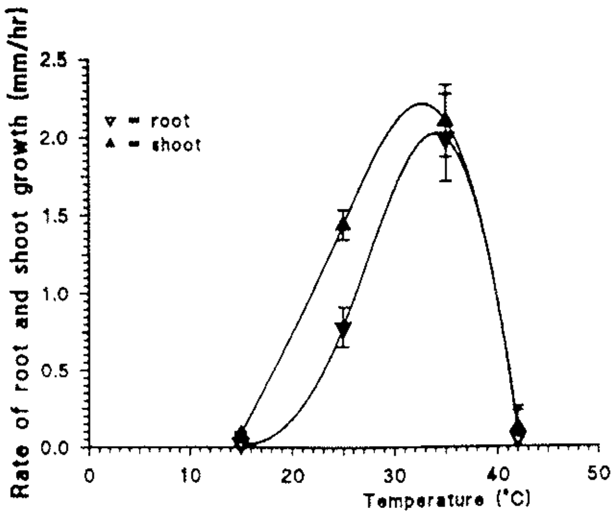


Cowpea cv. Vuli 1 (lot 2), % Germination (△) and Rate of Germination (▲) vs Temperature

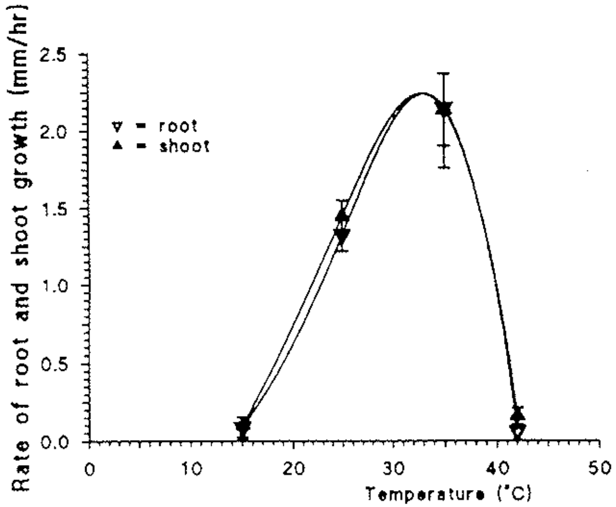
Fig. 3



Tegemeo, Rate of Root and Shoot Growth

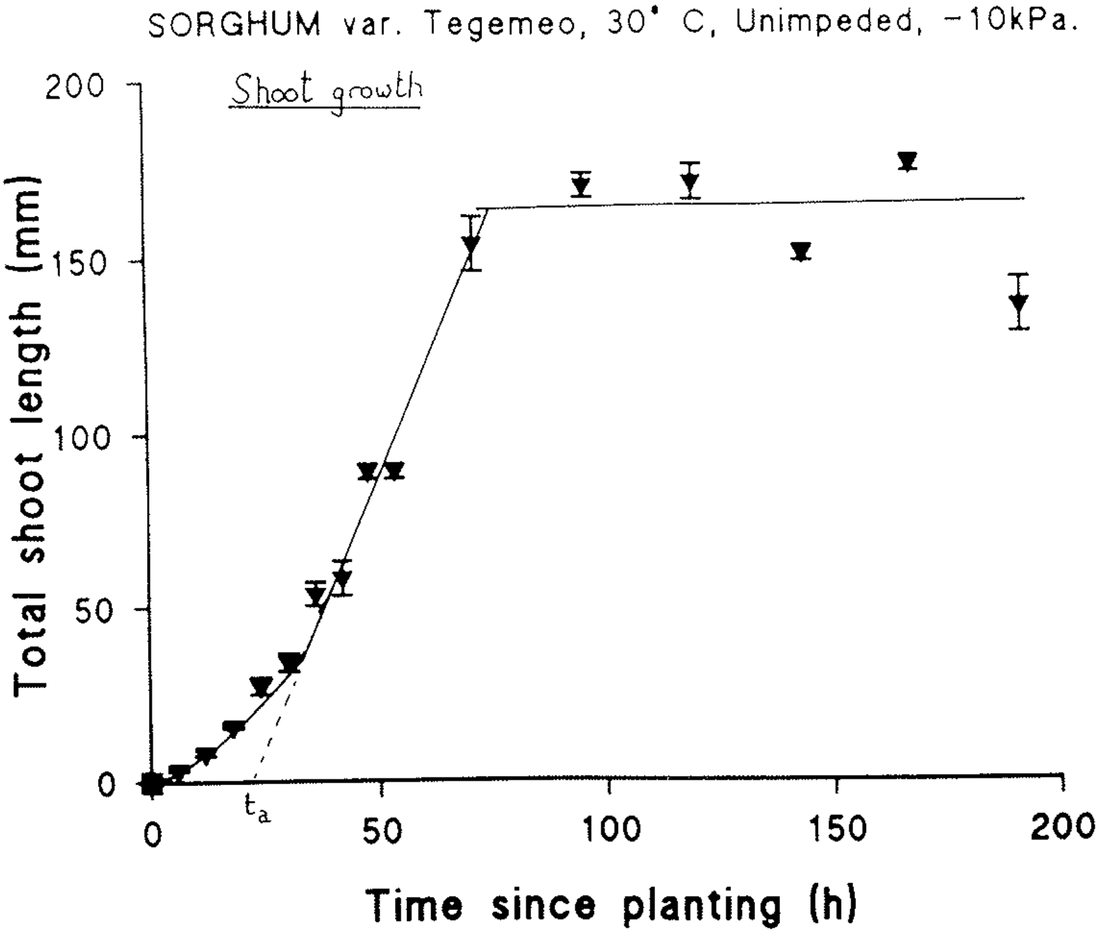


Mbangala, Rate of Root and Shoot Growth



Mbangala (aged to 70%), Rate of Root and Shoot Growth

Figure 4


SORGHUM var. Tegemeo, 30° C, Unimpeded, -10kPa.
Shoot growth
Total shoot length (mm)
200
150
100
50
0
t_a
0
50
100
150
200
Time since planting (h)

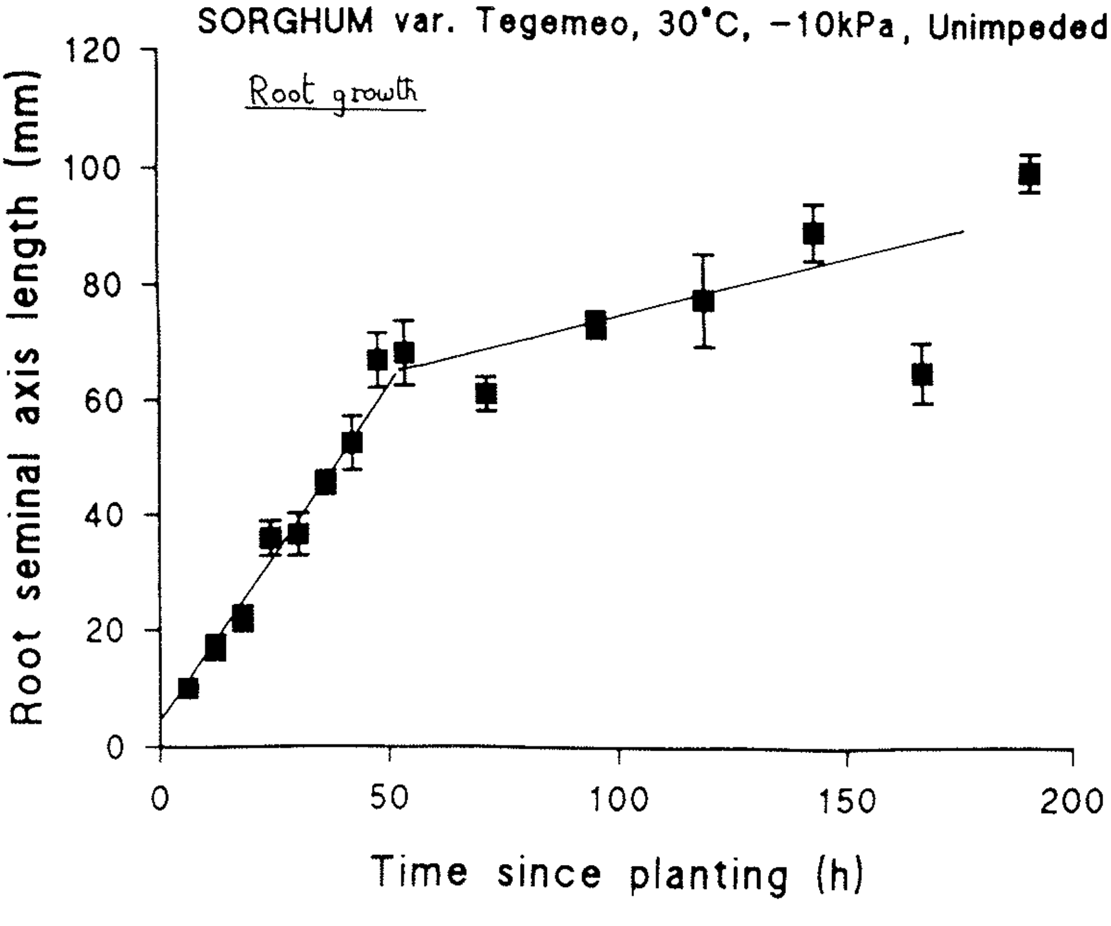
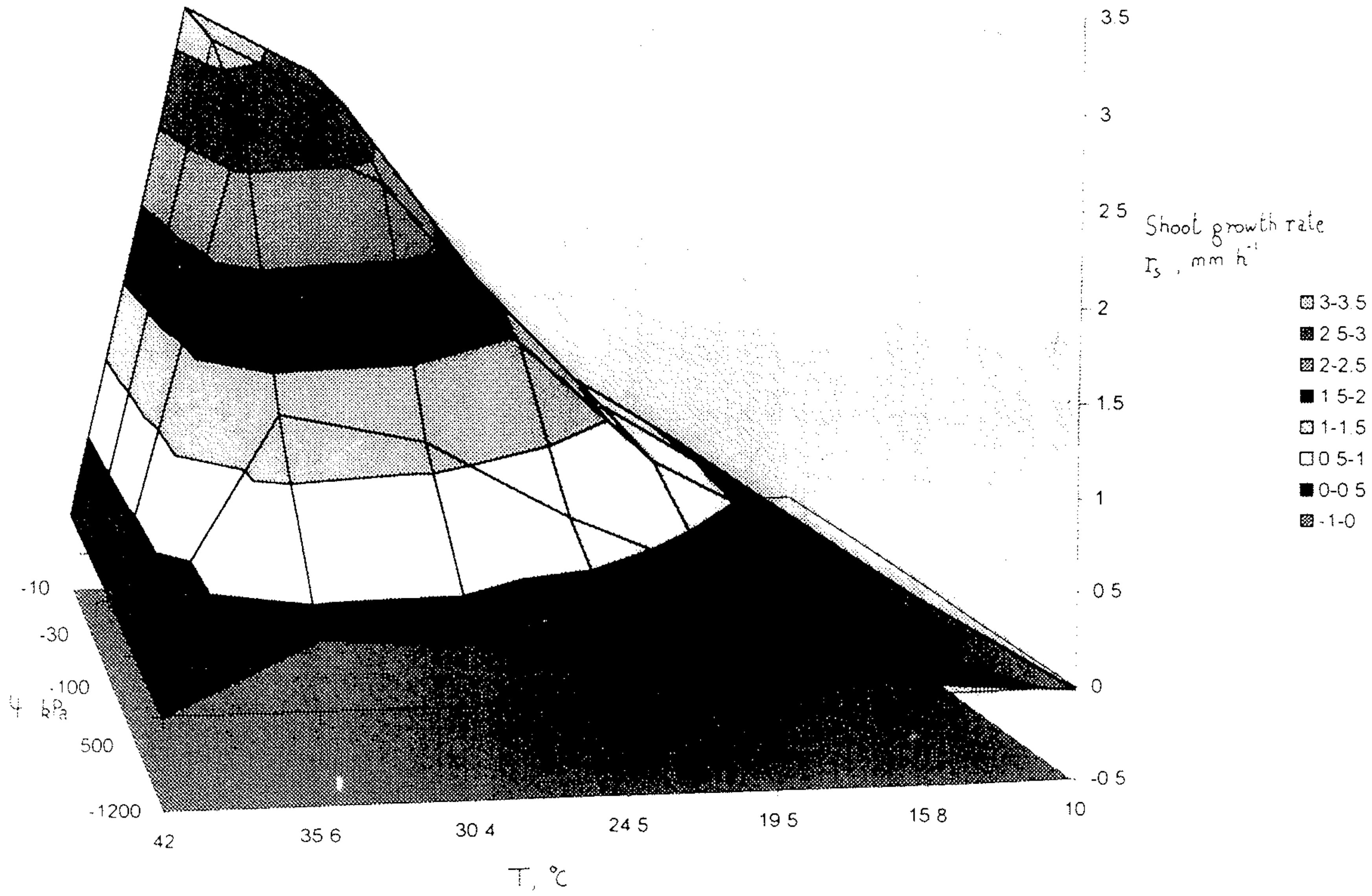
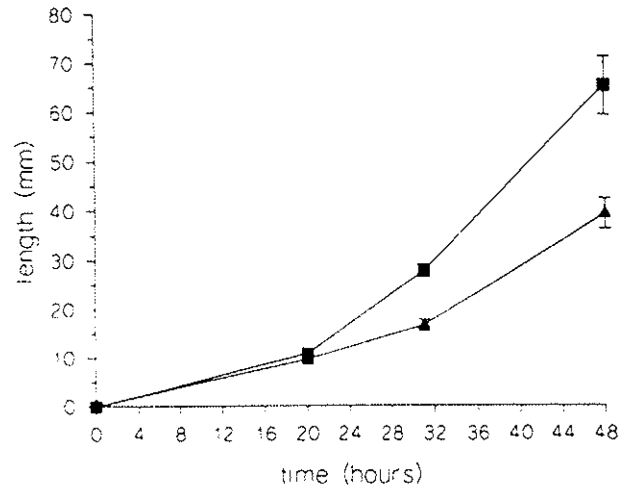

SORGHUM var. Tegemeo, 30°C, -10kPa, Unimpeded
Root growth
Root seminal axis length (mm)
120
100
80
60
40
20
0
0
50
100
150
200
Time since planting (h)

Fig 5 Sorghum shoot growth rate, model function



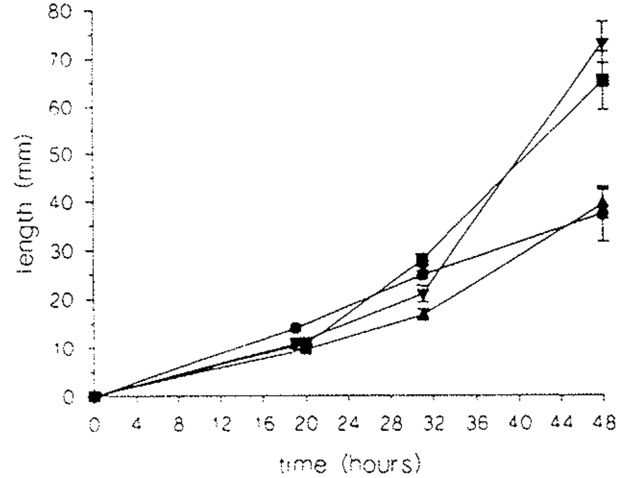
SHOOT GROWTH



■ -Unimpeded shoot (unimpeded root) ▲ -Impeded shoot (impeded root)

TEMPERATURE 32 C

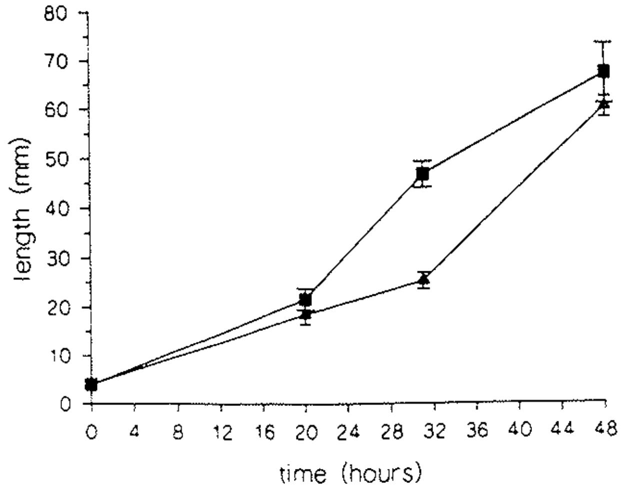
SHOOT GROWTH



▲ -Impeded shoot (impeded root) ▼ -Unimpeded shoot (impeded root)

-Unimpeded shoot (unimpeded root) ● -Impeded shoot (unimpeded root)

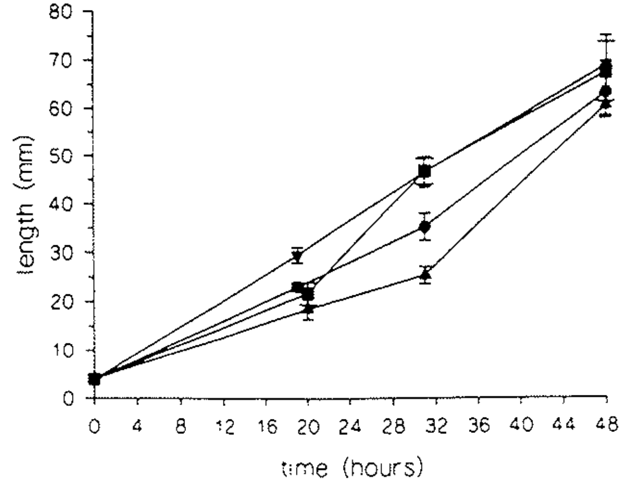
TEMPERATURE 32 C



■ - Unimpeded root (unimpeded shoot) ▲ -Impeded root (impeded shoot)

TEMPERATURE 32 C

ROOT GROWTH



▲ -Impeded root (impeded shoot) ▼ -Unimpeded root (impeded shoot)

■ - Unimpeded root (unimpeded shoot) ● -Impeded root (unimpeded shoot)

TEMPERATURE 32 C

Fig. 6 Sorghum (var. Tegemeo)
Effect of mechanical impedance on root & shoot growth