Current measurement techniques appropriate to agronomic research

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Introduction

Traditionally agricultural scientists have directed attention almost exclusively to measurement of effects of treatment on final yield. By contrast we now place a far greater emphasis on quantifying and understanding the processes contributing to yield. This has generally created the need for a more diverse and sophisticated range of measurements and measurement techniques than previously demanded in agricultural research. The processes influencing crop growth and development are the particular concern of scientists engaged in the diverse field of agronomic research.

In this paper we consider the purpose, types of equipment and methods of data recording and handling appropriate to modern agronomic research. Initially we developed a simple framework to encompass our understanding of the environmental and physiological factors influencing crop growth, and describe current techniques appropriate to their measurement. Rapid advances in technology have led to the widespread use of microprocessors and microcomputers in measurement systems, and we briefly describe their role in data acquisition and analysis. The review does not intend or attempt to cover all measurement techniques potentially available to the agronomist, for this is far beyond the scope of a single review. Although the techniques covered reflect our interests and background, they are considered to be of potential use to a wide range of scientists conducting agronomic research.

Framework for the Analysis and Measurement of Crop Growth

The rate of change in dry matter (dW/dt) of a crop over a period of time can be considered to represent the net effects of contributions of canopy photosynthesis (dP/dt) and respiratory losses (dR/dt). Thus crop growth rate, C, can be expressed as

$$C = dW/dt = dP/dt - dR/dt \quad . \ . \ . \quad (1)$$

Rates of canopy photosynthesis may be examined in terms of the ability of the crop to intercept and absorb incident photosynthetically active radiation (PAR) and the capacity of the crop to utilise absorbed radiation in the production of dry matter (1, 2). The expression:

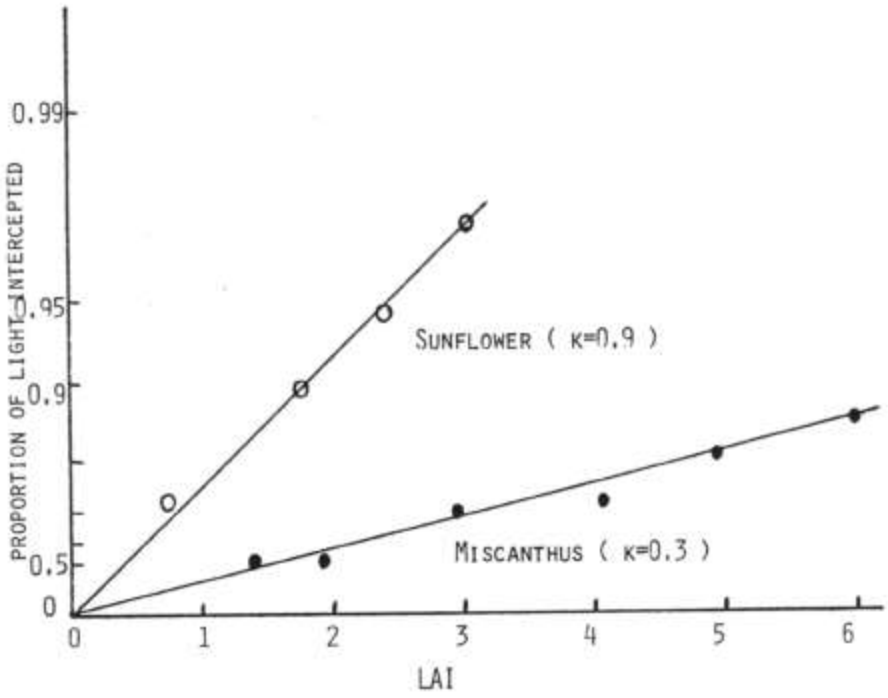
$$C = Qfc \quad . \ . \ . \quad (2)$$

describes these effects. Here Q is the PAR incident on the crop, f is the fraction of PAR absorbed and c is the efficiency of utilisation of absorbed PAR in dry matter production. A common unit for E is g DM MJ^{-1}.

C may be integrated over time to give the dry matter of the crop at a given time or stage of development, e.g. harvest. Yield of the harvested component of the crop may be analysed in terms of the harvest index, H, related to dry matter production at the time of harvest by

$$Y = H W_H \quad . \ . \ . \quad (3)$$

Figure 1. dependence of light interception an leaf area index far two contrasting canopies.



Here, H is the proportion of total dry matter production at harvest, WHO, realised in the yield component of the crop, e.g. grain, tubers.

f is controlled by leaf area, generally measured as the leaf area index, L, and its display. f is commonly related to L by

$$f = 1 - \exp(-KL) \quad \ldots \quad (4)$$

where K is an extinction coefficient. K is a useful measure of the light intercepting properties of a canopy. An example of the dependence of f on L for contrasting canopy structures is shown in Fig. 1.

Equations 1 to 3 provide a simple analysis of yield generation in crops where c , f, Q and H as affected by environment or treatment are considered the primary determinants of yield. Equation 4 emphasises the significance of leaf growth. As an illustration, agronomists interested in effects of plant density and spacing on crop performance are Likely to pay particular attention to effects on f and H under the assumption that c is not Likely to vary between treatments given adequate water and nutrition. The entomologist concerned with effects of leaf eating insects at different stages of growth will also focus attention on leaf losses and hence on f, while effects on H may also be important. c may change with environment in time of planting experiments, and in studies of effects of availability of water or nutrients. Plant breeders would be concerned with variations in r , f and H between cultivars.

The components of equations 1 to 4 are now considered and techniques appropriate to their measurement are discussed.

3. Measurement of Crop Growth Rate (C).

3.1 Dry Matter Harvests

Crop growth rate is commonly measured as the difference in dry matter production over an interval of time, often necessitating frequent harvests. These estimates necessarily neglect losses of dry matter through pests and diseases, and the root component is usually ignored because of the difficulties and labour involved in measurement. In general these estimates are only valid over periods of about a week and it is often difficult to ascribe differences to a particular cause.

3.2 Canopy Photosynthesis

On the basis of equation 1 crop growth rate represents the balance between photosynthetic CO_2 assimilation and losses through respiration. Measurements of net photosynthesis in the field are now more common in agronomic studies with improvements in technology and a greater awareness of the value of these measures (3). Canopy enclosures, measuring both rates of CO2 assimilation and canopy water use, provide a powerful tool in the understanding of crop response to environment and treatment. These systems provide estimates of crop growth over periods as short as five minutes, enabling immediate recognition of short-term changes.

In so called open systems of measuring rates of canopy gas exchange, ambient air is blown over a sample of crop enclosed by a transparent chamber (4, 5). Rates of CO_2 assimilation are derived from the rate of air flow and the depression in concentration of CO2 in the air as it passes over the crop. In closed systems, the concentration of CO2 in an air-tight chamber is maintained within predetermined limits by injecting pure CO2 to balance the loss in the system because of CO_2 assimilation. Rates of canopy CO2 assimilation are calculated from the quantity of CO_2 required to maintain the ambient concentration in the chamber (6, 7, 8).

Both these systems are expensive, generally requiring an air-conditioned van to house a range of instruments and gas flow controllers. Data acquisition and control is effected using computers. The chambers also require a means of cooling to maintain canopy temperatures within reasonable limits. Air-conditioning systems add considerably to their complexity and cost. The systems are also only semi-portable and are generally left in situ for several days. Adequate sampling is therefore a problem.

Rates of canopy assimilation and water use have also been determined over periods as short as a minute by measuring the transients in CO_2 concentration and water concentration generated within the chambers immediately after sealing the system (9). This enables the use of a single portable chamber to measure rate of gas exchange of a relatively large number of crops in reasonable time. Further development along these lines is expected with the advent of portable CO2 and water analyses such as those incorporated in the L16000 portable photosynthesis chambers available from LICOR, and CO_2 analysers from the Analytical Development Company England. Air conditioning of the chamber is not considered necessary because of the very short measurement period.

Measurement of Incident Light (Q)

Light energy in the wavelengths between 400-700 nm, commonly called photosynthetically active radiation (PAR) is of direct interest to agronomists. These wavelengths correspond with the visible spectrum and are effective in promoting photosynthesis. Standard meteorological stations record daily solar radiation with pyranometers which measure global short-wave radiation in the range 300-2600 nm. Daily radiation may also be estimated from Campbell-Stokes recorders measuring hours of sunshine. Hounam (10) describes relationships appropriate to Australian stations. Furthermore, PAR may be assumed to account for 45-50' the short-wave radiation (11). PAR may also be measured as the difference in output of solarimeters fitted with filters which remove the visible component, and solarimeters without a filter (12). Alternatively, PAR may be measured directly with quantum sensors insensitive to the longer wavelengths (e.g LICOR Ltd quantum sensor, LI19O5B).

Factors Influencing Fractional Light (f), and their Measurement

The amount of energy intercepted by a canopy depends on the radiant energy incident on the upper surface of the crop and the fraction intercepted (f), f is commonly related to leaf area index (L) and the light extinction coefficient (K) as shown by eq. 4.

5.1 Leaf Area Index (L)

Numerous direct and indirect methods of measuring leaf area for various crops have been developed because accurate measurements of L are laborious and time consuming. The methods have been summarised in recent reviews (13, 14, 15), and vary greatly in their precision, accuracy and difficulty. The choice of alternatives depends on the morphological features of the leaves, accuracy required, the amount of material, the amount of time and equipment available and whether destructive or non-destructive measurements are required. Two methods of measuring L are generally employed. Further detailed information on these particular methods is reported in ref 16. The first measures the area of all leaves directly using a digital electronic meter or planimeter (e.g LI-COR 3100). These are particularly appropriate to areas of leaves with irregular margins or those damaged by insects or hail. Area can be measured with these instruments with errors of less than 2%. The second method estimates leaf area as the product of leaf length, maximum leaf width, and a constant determined previously by regression. The calibration factor requires checking if leaf shape changes with position on the plant or with plant age. The advantage of this method is that repeated non-destructive measurements are possible on the same plants provided repeated handling and measuring does not reduce their growth. The leaf area of large samples may be derived from the measured area of a sub-sample and its specific leaf area (ie area per unit leaf weight).

5.2 Measurement of Light extinction coefficient (K)

K is very difficult to measure directly. As defined by eq. 4, it depends on the orientation distribution of the foliage elements and their relative dispersion on the plane normal to the direction of the sun. G therefore usually varies with solar position and hence diurnally. The orientation distribution of foliage elements may be computed from measurements of foliage angles made with a protractor (17), with point quadrants (18) and with the ingenious apparatus designed by Lang and Shell (19, 20). The effect of the dispersion of foliage elements on the plane normal to the beam direction may also be derived from point quadrats and measurements made with Lang's apparatus (20, 21). However the techniques are detailed and tedious, and direct measurement of K is not recommended for general agronomic studies. Techniques for indirectly estimating G will be discussed in section 5.4.

5.3 Measurement and Estimation of fractional light interception (f).

Direct methods of measuring f include the use of both mobile and stationary sensors (22). A small sensor is driven through the crop in the former, whereas tube solarimeters (2, 3) or line sensors of approximately 1.0 m length are employed in the latter. The sensor should respond only to PAR for growth studies. It should also exhibit an adequate cosine response in order that solar position does not bias the measurements. The line sensor measures f as the difference between the downward flux density of PAR incident on the crop, and the sum of the upward light flux density reflected off the canopy, and the downward light flux density transmitted to the soil surface. It therefore requires three measurements. Several sets of readings are invariably required to derive a reasonable spatial average.

The small mobile sensors are generally driven along a track at the base of the canopy, by hand or with a small electric motor. The sensor must exhibit a rapid response time. Measurements of PAR taken at the base of the canopy are compared with those measured above the canopy to derive f. This generally ignores upward reflection. These systems are necessarily linked to automated systems of data acquisition, and interrupts, generated at fixed distances as the sensor moves along the track, are employed to initiate readings. The entire operation of the apparatus is governed under computer control.

Communication with the sensor is generally a major problem as the data transmission lines typically foul the drive. Connor and Henstridge (unpublished) successfully designed a mobile sensor driven by a continuous loop of flexible wire which also acts as the data transmitter.

Given the difficulty of making direct measurements of K (section 5.2), direct measurements of f are strongly recommended where possible. f should be measured on several occasions during growth of the crop, and should preferably coincide with measurements of L. f may then be related to L using eq. 4. This equation is only applicable to continuous canopies, but is readily adapted to cope with spatial heterogeneity as exhibited in row crops. In this case, an estimate of fractional ground cover (f0) is needed, or preferably an estimate of the maximum possible fraction of shade on the soil surface during the middle of the day (24, 25). Here eg. 4 becomes

$$\underline{f} = \underline{f_G}\ [1-\exp(-KL/\underline{f_G})] \qquad (5)$$

When the exponential term in eg. 4 approaches zero at large values of L, interception is complete. In eg. 5, maximum fractional interception is f_G. Light interception in row crops thus often depends on increase in 1_G and its maximum value, as contrasted with changes in the exponential term. In this case, f_0 and hence f may be amenable to simple measurement for example by ruler, or even visual assessment.

The relationship describing the dependence of direct measurements of f on 1_G and L should be sought in field agronomic studies, as they provide indirect estimates of K (26). These estimates and relationships provide a sound basis for comparison between treatments. In addition, in the absence of extreme or unusual effects of treatment, these relationships should prove valuable as a basis for estimating f in subsequent experiments carried out using the same species and cultivars and the latitude and time of year the data were collected. For example, Wright et al (27) were able to take advantage of relationships developed by Muchow et al (28) to estimate f from measurements of L in grain sorghum. Monteith (22) presents estimates of K based on eg. 4 for a range of crops.

6. Efficiency of Light Utilisation(ε) and its Relationship to Activity of Individual Leaves

The slope of the curve relating dry matter production and intercepted light (Fig. 2, Eg. 2), or CO_2 assimilation and intercepted light (Fig. 3 , Egs. 1, 2) is the efficiency of utilisation of PAR in dry matter (ε DM) and CO_2 assimilation (ε CO_2) respectively. Thus ε is not determined directly, and varies with the means of determining C. In particular ε DM often does not include the contribution of roots to total dry matter production. ε CO2 includes total canopy assimilation, but, in so-called open systems of measuring gas exchange (section 3.2),does not account for root respiration losses of CO_2, as a positive pressure is maintained in the chambers to remove effects of soil respiration from the measurement of canopy CO_2 exchange. Despite their derivation, estimates of E depend on factors such as the orientation of foliage elements in the canopy (ie K), rate of canopy respiration and leaf resistance to CO_2 assimilation. K influences both the distribution of light in the canopy (eq. 4) and the rate of individual leaf photosynthesis in <u>situ:</u> leaf photosynthesis responds non-linearly to irradiance, and the irradiance at the leaf surface depends on leaf-sun angles (21, 29, 30). High rates of canopy respiration decrease ε. The rate of assimilation of CO_2 by individual leaves (A) is one of the most important determinants of ε. The resistance r', of individual leaves to CO_2 assimilation is measured as (31, 32):

$$r' = \Delta c'/A \qquad \ldots \qquad (6)$$

where Ac' is the ambient concentration of CO2 in the air surrounding the leaf. r' involves additive resistances in series, comprising contributions associated with the boundary laver of leaves (r'a), stomatal resistance (r' s) and the residual internal resistance, r'int (33). As these are in series (see Fig. 4):

$$r' = r'a + r's + r'int \qquad \ldots \qquad (7)$$

r'int includes a resistance to liquid phase diffusion inside the cell and a resistance associated with the photosynthetic process (33). r'a is generally small in relation to r'a and r' int under field conditions. Furthermore. r' int is often small in comparison with r 's (34). r'a thus provides one of the major limitations to the rate of CO_2 exchange of a canopy. r'a varies with irradiance (33), whereby stomata close at night,

and also increases with moisture stress (35). Increases in r'int and r'a have also been associated with nutrient deficiencies (36, 37).

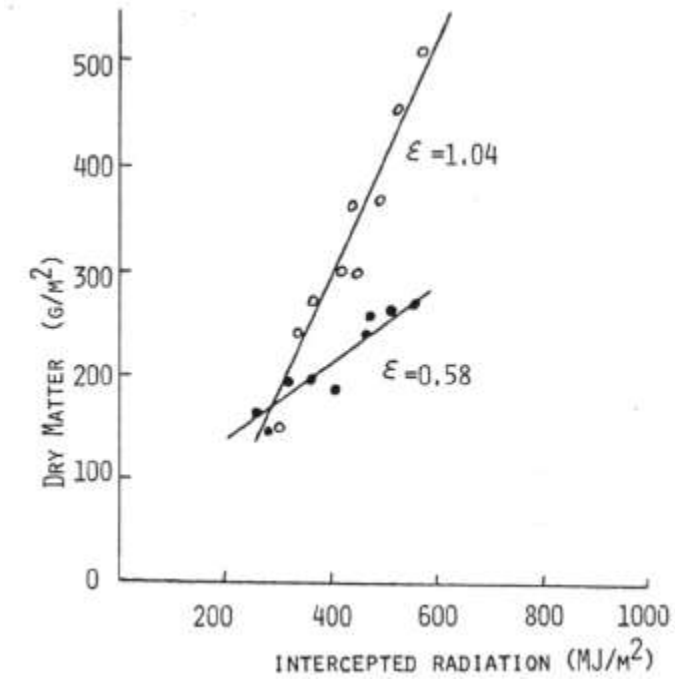


Figure 2. Relationship between maximum dry matter production and intercepted radiation throughout the growth of a pigeon- pea crop under irrigated (o) and dryland(.) conditions.

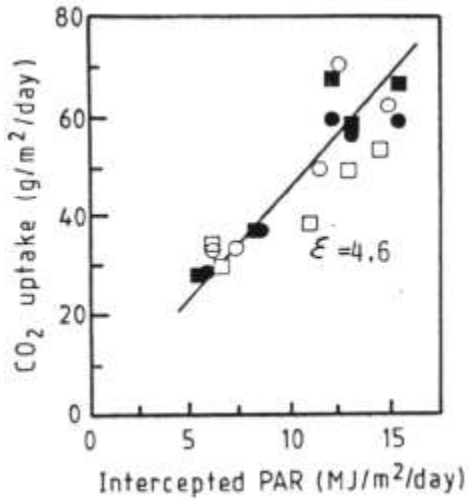


Figure 3. Relationship between daily CO_2 uptake and intercepted radiation for a lucerne crop. Ref 87.

The stomata are also a major control of rate of water loss from the leaves. The rate of transpiration. E is given by

$$E = \Delta c/(rs + ra) \quad \ldots \quad (8)$$

where ,L^{a}c is the difference in concentration of water vapour between the substomatal activity and the surrounding air. rs is directly related to is by (33).

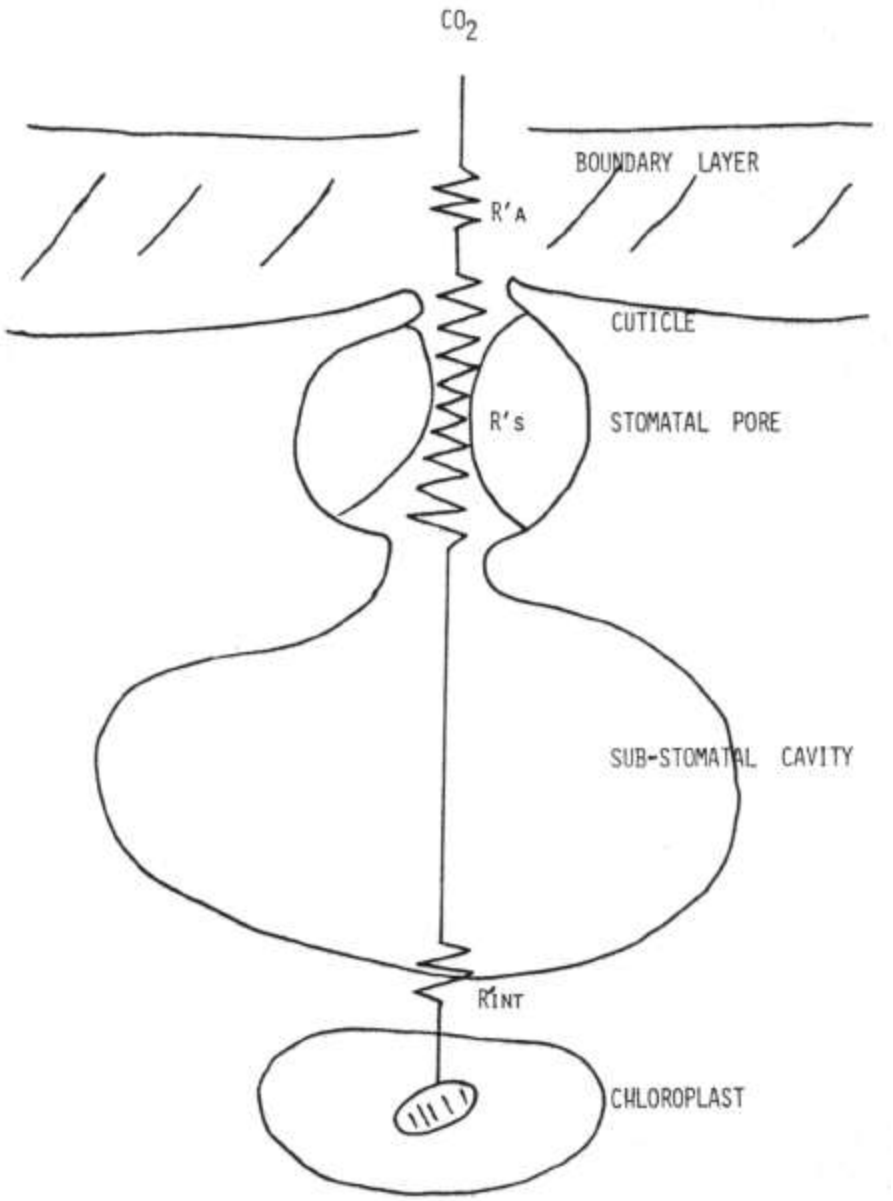
$$r_s = r's/1.65$$

6.1 Measurement of Leaf Resistances to Gas Exchange

Measurement of rs usually provides the means of estimating r's. rs is commonly measured on upper, active sunlit leaves with diffusion porometers or, more recently, with null-point porometers. Diffusion porometers measure the rate of humidification of unstirred air surrounding a portion of leaf enclosed by a small hand-held chamber. rs is derived from these rates via calibration. The instrument made by Delta-T Devices has been used successfully at Tatura for several years. The null-point instrument (LI-1600), manufactured by LI-C0R Ltd, measures both rates of transpiration and rs directly. These are derived from the rate of supply of dry air required to maintain a present humidity in a stirred, hand-held chamber clamped to a leaf. These instruments are considerably more expensive than diffusion porometers but offer the advantages of direct output and eliminate the need for calibration plates. A microprocessor controls operation of the porometer and the calculation and display of data.

Portable instruments measuring both rates of leaf photosynthesis and transpiration are the latest developments in this area. Thus all the components of eq. 7 are available as well as E and A. 0ne is made by LI-COR Ltd (LI-6000) and another by the Analytical Development Company. These measure E and A by the transients generated in concentrations of CO_2 and water effected by closing the system when the stirred chamber is clamped to the leaf. The LI-COR instrument makes extensive use of microcomputer technology. The expense of these instruments currently precludes their widespread use in agronomic research, but, with anticipated improvements in technology their cost is likely to become less prohibitive.

Figure 4. The resistances to co2 in a leaf.



Each of these instruments is portable, non destructive and sampling is sufficiently rapid to enable measurements of variations within and between treatments. However, care must be taken in the interpretation of results, particularly with extrapolation of singie-1eaf activity to the entire canopy. Time of sampling during the day is also important where the main concern is comparison of treatments: activities depend on irradiance, and diurnal variations associated with the onset of moisture stress are also important (38). They do however provide an excellent means of studying major sources of variation in r. and are invaluable tools in the study of canopy water relations.

Techniques of measuring E and A using $^{14}CO_2$ and tritiated water have also been employed. These are generally less popular than the previous techniques -because of the need to handle radio isotopes, and measurement is destructive. Rates of photosynthesis have also been measured with the Shimshi apparatus (39), and rates of E and A are measured using the dual isotope technique (40).

7. Measurement of Harvest Index (H)

H is commonly measured as the ratio of crop grain yield to the total above-ground dry matter of the crop at harvest. H provides no information on the development of the yield component. A more detailed understanding of yield development in crops can be achieved through frequent dry matter harvests of the yield component. Non-destructive measurements of development of the yield component may be achieved by measuring change in dimension of the organ concerned. This can be carried out manually, or by the use of displacement transducers.

7.1 Use of Displacement Transducers for Measurement of Change in Plant Dimension

The displacement transducer, more commonly known as the linear variable displacement transducer or LVDT, is a simple device with voltage output proportional to the displacement of a lightly weighted plunger. It is designed to be extremely sensitive to displacement but insensitive to ambient environmental conditions. It is suitable for accurate, in situ and non-destructive recording of for example head or fruit growth over periods of hours (41). The output can be continuously measured and analysed through data acquisition systems. Displacement transducers have also been used extensively in field and glasshouse studies where leaf and stem expansion have been monitored (for example ref. 42 and 43). In a different context they have also been used to infer leaf water potential changes from stem diameter fluctuations (44, 45).

In the previous discussion we have shown how crop growth can be affected by physiological processes such as expansive growth, stomatal function and leaf photosynthetic performance Additionally means of quantifying crop water and nutrient status is essential. In this section techniques available for the measurement of crop and soil water status are described. Techniques for the measurement of crop and soil nutrient status are omitted. They have been exhaustively reviewed elsewhere, for example ref. 46.

8. Measurement of Crop Water Status

The two basic parameters which describe the plant water deficit are water content expressed relative to full saturation (relative water content, RWC), and the energy status of water in the cell expressed as total water potential (T). Although the two parameters are linked with decreases in T following decreases in RWC, the relationship between them is not unique but varies with species, environment and history of stress. Thus for detailed studies both RWC and T need to be measured (47).

8.1 Relative Water Content

RWC is measured by placing leaf discs into an hermatically sealed tared vial. After measuring the fresh weight (FW) the discs are floated on distilled water for several hours until fully turgid. They are then surface dried and weighed (TW), and dried to give their dry weight (DW) (48). RWC is calculated from

$$RWC = \frac{FW-DW}{TW-DW} \times 100 \quad \ldots \quad (9)$$

8.2 Total Water Potential and its Components

ψ at any point in the plant can be partitioned into osmotic (r), turgor (P) and matric (T) components. Neglecting matric components (49), T is given by

$$\Psi = \pi + P \quad \ldots \quad (10)$$

ψ has gained prominence as the main measurement of plant water status because of its importance as the driving force for water movement through the soil, plant and atmosphere. The state of water in the soil-plant-atmosphere continuum may be expressed in terms of energy or potential (50). The main advantage of this concept is that it provides a unified measure describing the status of water anywhere within the continuum. Water potentials in the plant are also relatively easily measured. However there is

no proof that ψ has any direct effect on physiological processes. Indeed it is the independent effects of the turgor and osmotic components that have received attention in recent times.

Presently thermocouple psychrometry and the pressure chamber technique are widely used for the determination of Y. The thermocouple psychrometer is based on the principle that the relative vapour pressure (e/e_o) of plant tissue is related to its water potential by

$$\Psi = \frac{RT}{\bar{V}} \ln e/e_o \quad \ldots \quad (11)$$

where R is the gas constant, T is the Kelvin temperature, V is the partial molar volume of water. e is the vapour pressure of water in the tissue and e_o is the vapour pressure of pure water at atmospheric pressure. Plant material allowed to equilibrate in a sealed chamber generates a vapour pressure in the chamber equivalent to the total water potential of the tissue. The vapour pressure is measured by condensation of a droplet of water on a thermocouple inside the chamber, by Peltier cooling, and measuring the wet bulb temperature depression associated with evaporation from the droplet after the cooling current is withdrawn (51).

Reviews on the many modifications and improvements to thermocouple psychrometers can be found elsewhere (52, 53). Temperature-compensated thermocouple psychrometers have also been developed for in situ measurement however their use in field studies to date has been limited (47).

The general requirement for strict temperature control has restricted the use of uncompensated thermocouple psychrometers in field studies to situations where good laboratory facilities are close to the experimental sites; air conditioned caravans may be adequate for field work. Long equilibration times and the expense of commercially available psychrometers have also limited widespread use. In the facility at Tatura, psychrometers have been manufactured on-site, cutting expense and enabling easy repair and replacement. Chambers of different shapes and sizes can be constructed to accommodate different tissues. For example we have measured water potentials of leaf, stem, head, root and nodule tissue. Sampling is simple and rapid. Many samples can be quickly collected from the one plot, and included in a single chamber. This assists in coping with spatial variation within treatments. The facility is a powerful, low cost and labour saving technique for measurement of ψ (and its components).

The pressure chamber technique (57) has been widely adopted because of its ease of use, its speed and reliability and the fact that it does not require fine control of temperature. A leaf is excised from the plant, sealed in the chamber with the petiole protruding and pressure applied until xylem sap exudes from the cut surface. The pressure applied is taken as the matric potential of the water in the apoplast or cell wall of the tissue (49). This assumes that the matric potential is in equilibrium with the total water potential of the leaf cells, and that the osmotic potential of the apoplastic water is near zero. The technique has been extensively reviewed by Ritchie and Hinkley (58). Turner (47, 59) has demonstrated the need to enclose the leaf sample in a plastic bag before excision, in order to minimise evaporative losses and hence errors in measurement.

8.3 Estimates of Terror (P).

Many physiological processes such as leaf expansion, leaf wilting and rolling, stomatal opening and associated photosynthesis are directly affected by a reduction of P which accompanies the loss of water from leaf tissue (35). Thus P will directly affect both f and c in eq. 3 through a variety of the above processes.

P is most widely measured by estimating from measurements of Y and r from eq. 10:

$$P = \Psi - \pi \quad \ldots \quad (12)$$

thus, it is important to have reliable measurements of n in order to estimate P. r can be measured by refractometric, cryoscopic, psychrometric and pressure chamber techniques. Of these the psychrometric and pressure chamber techniques are the most widely used in agronomic research. Readers are referred to papers by Shimahj and Liune (60) for refractrometric, and Barrs (52) for cryoscopic methods of measurement. Measurements of 7 can be made using thermocouple psychrometers by either expressing sap onto filter paper, or using frozen and thawed tissue (47). With the pressure chamber, P is reduced to zero by applying pressure to the tissue and obtaining a from the pressure-volume relationship of the intact cells. Once P reaches zero, the volume of water in the cell is related to applied pressure by:

$$\frac{1}{P} = \frac{Vs - V}{RTN} \quad . \ . \ . \quad (13)$$

where P is the pressure in the chamber, Vs is the volume of intracellular water in the turgid tissue, V is the volume of intracellular water expressed, R is the gas constant, T is the Kelvin temperature and N is the moles of solute in the leaf. Thus a plot of 1/P against V, (or RWC) should be linear when P becomes zero. Extrapolation of the straight line, V=0, gives π at full turgor, and the π at zero turgor is the point at which ψ?=?π These estimates of π have been criticized as they are based on a dubious linear extrapolation of the pressure/volume curve to a water potential of minus infinity (62).

9. Measurement of Soil Water Status

The need to determine the amount of water contained in the soil arises frequently in many agronomic investigations. This information is a requisite for understanding the soil chemical, mechanical and hydrological behaviour. and the growth response of plants.

Direct and indirect methods to measure soil water content and potential have been extensively reviewed by Gardner (63). Soil moisture can be measured gravimetrically or monitored indirectly using gypsum blocks, neutron scattering, tensiometers and by thermocouple psychrometers. With all these techniques the water content and/or potential is only measured in the immediate vicinity of the measuring unit, and because of the enormous soil heterogeneity large numbers of measuring sites, access tubes etc —.are required to give a reliable spatial average.

Gravimetric sampling for direct determination of water content is simple but time consuming and can therefore be expensive. The errors of gravimetric sampling can be reduced by increasing the size and number of samples. However the sampling method is destructive and may disturb plots. For these reasons many workers prefer indirect methods which permit making frequent and continuous measurements at the same points, and, once the equipment is installed and calibrated, with much less time and labour.

Gypsum blocks are simple and inexpensive. The main difficulty is the uncertainty in calibration. Water content or potential is inferred from measurements of electrical resistance. The calibration varies between blocks and with soil type, with time and changes in the electrical conductivity of the soil solution. It is there for difficult to interpret readings quantitatively in terms of water stored or water lost. They can, however, be useful as a relative measure of soil moisture status.

The neutron probe is widely used for soil moisture measurement and has been extensively reviewed (64, 65). Recent improvements in neutron probe design have minimised radiation hazards, cost and maintenance problems and led to its widespread use amongst researchers, farmers and consultants. The use and application of the technique to field studies is discussed further by Cull (66).

Tensiometers are frequently used to measure soil matric potential in the field. They have the advantage that they are relatively simple and inexpensive. However they are limited to potentials greater than -0.1 MRa and require frequent servicing.

Soil water potentials have been measured in the glasshouse (67) and field (68) by thermocouple psychrometers. Their advantage is that an extensive range of potentials may be measured (range -0.1 to -8.0 MPa) (69). However, their use in field studies has been limited, possibly because of the cost of commercial units and problems with contamination once installed in the soil. More research aimed at improving their design and operation in the field would be worthwhile to enable automated measurements of soil water potential.

10. Canopy Temperatures in Relation to Crop and Soil Moisture Status

The tedious and impractical nature of many of the scientific methods of measuring crop and soil water status severely restricts their application in many agronomic studies and also in irrigation scheduling. Infra-red thermometers which measure foliage temperatures now provide a rapid, non-destructive method of measuring stress, and hence inferring canopy water status and activity. A crop water stress index, dependent on vapour pressure deficit, has been derived from air-canopy temperature differentials (70, 71). These indices have been shown to be well related to available soil moisture (70) and also to yield during heading and maturity (71). Infra-red thermometers have also been used to infer transpiration rate, stomatal resistance and leaf mesophyll resistance to CO_2. Smith (72) discusses these possibilities, and provides an indication of their potential use in agronomic research.

11. Measurement of Root-Growth

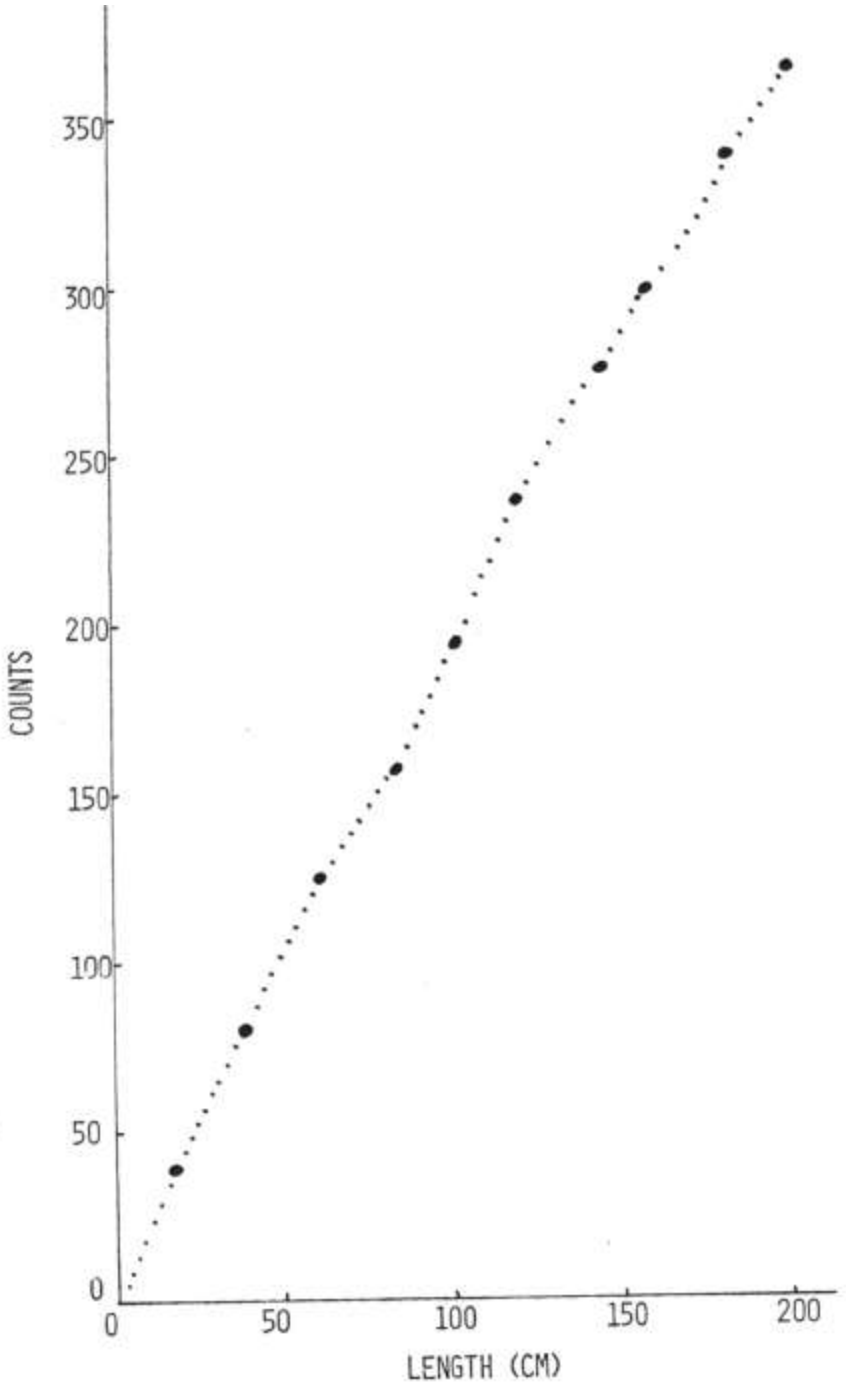
For a thorough understanding of the development of a crop both the above and below ground portions of the plant must be included. The root system plays a crucial role in the growth and development of the plant, especially when water and nutrients are limited. The total length and distribution of the root system (root length density) are considered the most important factors influencing the ability of the plant to absorb water and nutrients (73).

The technique for estimating root length as originally described by Newman (74) involves the counting of intersections of root and a grid pattern. A typical calibration line relating root length to the number of counts is shown in Fig. 5. In field studies root length may be measured destructively by the core method, or non-destructively using mini-rhizotrons (75). As for the soil water status measurements discussed above, these techniques suffer the problem of not adequately accounting for spatial variability within the soil. The problem is unfortunately only overcome by increasing the number of samples taken within a particular plot. The relative benefits and modifications of both methods will be briefly discussed.

11.1 Core Method

The core method provides a basic illustration of the Newman method. It has been widely used in many field studies and involves washing and sieving root material from a core or microplot sample. Roots are then evenly spread over the grid and the number of intersections of roots with the grid are counted. Equally, photographs can be taken and the negatives projected onto a horizontal screen etched with a standard grid for counting at a later stage. Several researchers have reported the development of apparatus to automate the tedious and time-consuming counting procedure. Richards et al (76) have developed a machine for determining root length where a light bean and detector traverse a spiral path across the sample. Intersections with roots are detected with a light sensitive diode and electronic circuitry is used to compute root length. Current advances in this area use video cameras. Henstridge (unpublished) has analysed video images directly to determine root length of a sample displayed on a tray. Barrs (77) digitises the output from the video camera using a microcomputer. His apparatus can also be used to measure root area which then enables the estimation of average root diameter. The microcomputer can also be programmed to recognise varying shades or colours and can therefore differentiate between dead, diseased or live root tissue.

Figure 5, root length calibration curve,



11.2 Mini Rhizotron Method

The mini-rhizotron provides a technique for direct root observation in the field, which can be used repeatedly at a particular point in time. The basic technology for the system was originally described by Waddington (78). Briefly the instrument is composed of a light source, a flexible optical fiberscope, a clear tube inserted in the soil and an objective lens that transmits the subject image to a focusing eye-piece (Fig. 6). The observation of roots intersecting a mini-rhizotron may be accomplished by a field observer who makes appropriate counts or measurements directly, or a picture may be made and analysed later. Dyer and Brown (79) proposed the use of a video camera and recorder. Barrs (77) is currently assessing the potential of image analysis to process root length data collected as video images on a tape recorder

connected via a TV camera to an optical fibrescope inserted into a mini-rhizotron tube. Upchurch and Ritchie (80) have also described a mini-rhizotron system which is constructed in such a fashion that it can be used as a neutron access tube, allowing water content and root density measurements to be made at the same point in the profile.

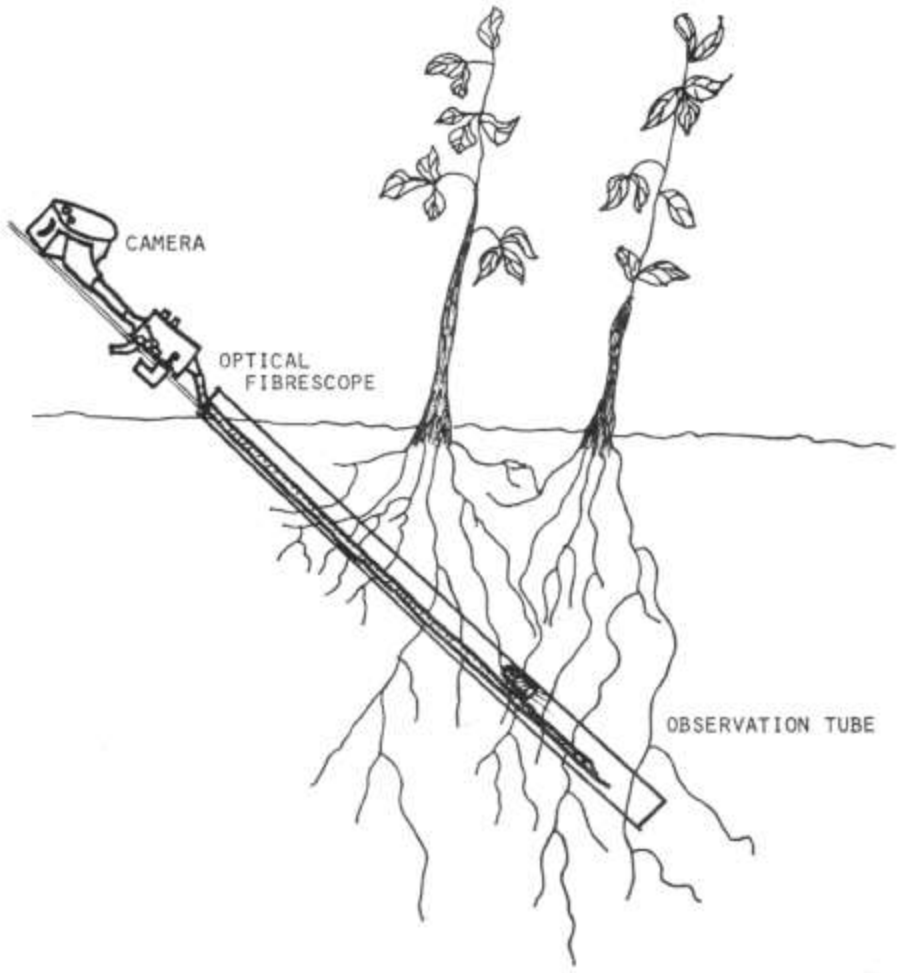
12. General Methods of Automatic Data Acquisition

The need to minimize time and labour commitments has generally encouraged scientists to automate data acquisition and recording wherever possible. In the past, this generally involved transducers linked to multichannel chart recorders and/or paper tape punches if a computer was available to process the data. Integrators, providing averages over time, were often used to effect data reduction. Magnetic tape was also used for data storage where computers were available 'on-line'. However, access to such complicated expensive systems was available to few agronomists, largely as a result of their cost, but partly as a consequence of their location in remote areas with little or no access to servicing facilities. The need for expertise in programming provided a further obstacle even when computers were available.

Today, these restrictions no longer apply, and almost all agronomists have access to relatively powerful, inexpensive computing facilities. The micro-processor, employed in microcomputers and data acquisition modules (DAM), has revolutionized data acquisition and control. A wider range of more reliable and often cheaper transducers and instruments is also available, providing greater flexibility and scope than previously available in the field of agronomic measurements. The use of microcomputers as replacements for pen and pencil in the collection of field data is described in these proceedings by Berry (81). Workers from Horsham have also described their use in collecting weights and penetrometer data (82, 83).

Most of the elements of a micro-computer based data acquisition system are shown in Figure 7. Transducers and instruments are connected directly to the DAM. The DAM may be located near the sensors at a considerable distance from the computer depending on the communications employed. The transducers

Fig. 6. the components of a mini¨rhizotron placed in the field.



may include temperature sensors. such as the monolithic type now commonly employed in agronomic studies, humidity sensors involving, for example, measurements of dry bulb temperature and wet—bulb depression via thermocouples (84, 85) or PAR sensors such as the LI190SB from LICOR. The instruments may be any of a wide range with voltage or current output. These are connected to the multiplexer inside the DAM. Some Dam's also handle digital input. This may be data, an input indicating the status of a controller, or a counter such as employed on tipping bucket rain gauges. Digital output is also generally available for control of remote facilities, for example, switch solenoids and instruments on and off.

The multiplexer selects one input at a time for processing, being functionally equivalent to a multiposition switch. This connects the selected input to the amplifier or signal booster.

Many sensors output only low signal voltages or currents and so require amplification to more manageable levels. The amplifier must be capable of handling all the types of sensors employed. Input signal may need to be filtered to reduce noise to an acceptable level prior to amplification. Once amplified, the signal is presented to an analogue to digital converter (ADC), generally a device that accepts analogue information, as a voltage, and converts it to a coded digital output as required by the computer. It is the heart of a data acquisition system. There are several techniques of effecting the conversion with consequential effects on conversion rates. accuracy, noise rejection, temperature stability, complexity and cost. Resolution and speed are important. The resolution of an 8-bit ADC is 0.5 , whereas that of a 16 bit ADC is 0.002 . 8-bit conversion is often adequate but 12 or more bits provides greater scope for handling a range of sensor inputs. Speed is generally not a problem in agricultural

experiments, where 1 sample per sec is often adequate. Unnecessary speed is expensive and may increase noise problems.

The coded output of the ADC is transferred to on-board memory components for subsequent retrieval, or available to the communications section for immediate transfer to the computer.

Interfacing to the computer is often straight forward but problems can arise. Interfacing standards are still imprecise and are frequently not adequately supported by high level computer languages. The RS232 serial interface is one of the most common. This is a three-wire communication link in its simplest form. Data are transferred one bit at a time. Software support from languages such as Basic varies widely between micro-computers, as does the ease of sending and retrieving data. Depending on the DAM, commands and data may need special coding and decoding respectively.

As shown in Fig. 7, peripherals attached to the computer provide for data storage ('floppy' disks, 'hard' disks. magnetic tape), visual appraisal of the data (printer, plotter, video display unit) and data manipulation and analysis. The computer is now often a relatively cheap microprocessor-based machine. Some are portable enabling deployment or use in the field. For ease of use and the ability to manipulate data and files, microcomputers with the CPM-based MSDOS or CPM86 operating systems offer considerable advantages over alternatives.

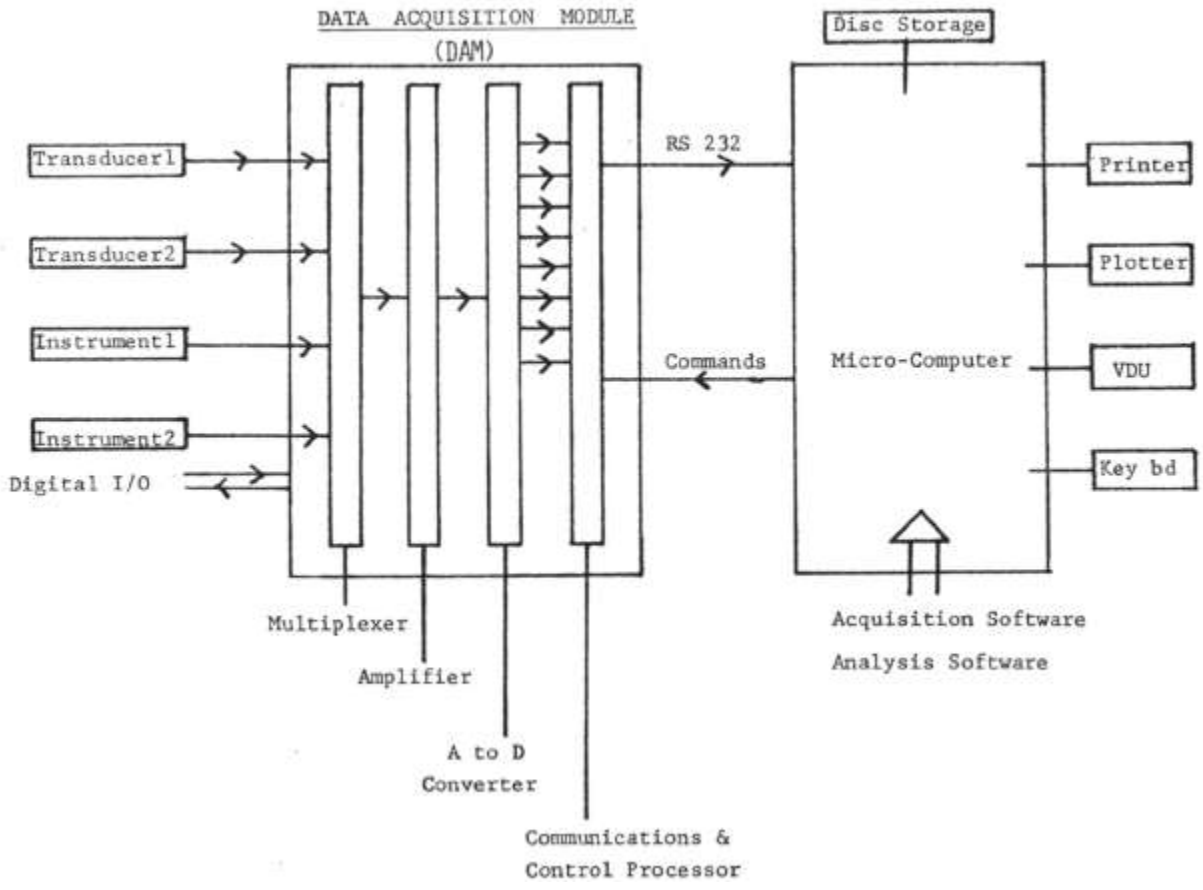


Figure 7. The components of a data acquisition system.

Control of the acquisition sequence may reside in the computer or on the DAM. In the former, commands are sent to the DAM, which immediately processes the request, and automatically transmits the required

data back to the computer. The command must specify an address if several DAM'S are deployed in a network, the channel or transducer and its appropriate range and mode e.g. - 165 ˉ1- +2 m V , O-10G , 0-10mA). The computer must be able to recognise and act on problems associated with a break in communications, data over range and transducer malfunction. It is relatively simple to 'hang-up' the computer during data acquisition, and just as easy to collect nonsensical data. A clock is required in the computer if data acquisition is to occur in 'real' time. Commands had to be coded prior to transmission and data decoded in earlier unsophisticated systems. This was necessary to minimise the intelligence required of the DAM. Current Dam's such as the 'Dataporte', manufactured by Data Electronics (Aust) Pty, Ltd, employ an 'on-board' microprocessor to interpret a much more complex command structure. They also use 'on-board' random access memory for intermediate data storage, and provide an 'on-board' clock. The more complex command structure in fact permits the use of simpler commands from the user's point of view to effect control of the DAM. For example, the DAM is able to accept mnemonics such as

RIOM, 1...5V

to enable voltage readings every 10 minutes on channels 1 to 5, as compared with the necessity to build a specific bit structure in the word or words sent as commands to the DAM. The need to control scan intervals from the computer effectively ties up the use of the computer which must be dedicated to the acquisition task. The use of mnemonics (or whole words) to effect the command further enables the user to take advantage of several excellent commercial communications software packages to program the DAM and retrieve the data. This eliminates the need to write specific programmes for each and every task. These are significant advances over earlier systems, which demanded programming expertise and an extensive involvement with the intricacies of command structure data formats and additional problems with real-time data acquisition sequences. Whilst problems will always arise, the emphasis now resides in the choice of measurement, choice of sensor or instrument and their disposition, choice of appropriate scan intervals and analysis of the data.

13. Conclusions

Even without the automation of data collecting and processing, the formulation of critical questions and the selection of the pertinent measurement techniques is an essential part of agronomic research. For instance. there is often the danger that computer-based data acquisition systems may give great impetus to research that has no theoretical background. Rather, automatic data processing should allow researchers to design more comprehensive experiments to answer specific hypotheses. The time released by such useful application of automation should then allow the researcher to contemplate his aims, methods and results more critically.

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