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ABSTRACT

Much of the current research in experimental plant biology requires highly uniform plants. To achieve this, many plants are grown under conditions in which the environment is carefully manipulated. This pamphlet has been prepared, therefore, to present and describe growth procedures which will produce vigorous, healthy, uniform plant material in regulated environments for experimental purposes. The publication is intended for those with some knowledge of plants who want to grow one or more species for experimental purposes, for demonstrations in schools, or for science projects where limited facilities are available. Topics discussed include: (1) control of environment--greenhouses, growth chambers, and seed germinators, (2) factors for plant growth--light, temperature, relative humidity, growth media, and nutrition, (3) germination of seed--two methods, (4) transplanting, (5) culture techniques--containers, aeration, subirrigation, and nutrient solution, and (6) techniques for specific plants. An index to more than 50 plants mentioned in the text is also given. The techniques and equipment described are those used at the Metabolism and Radiation Research Laboratory, Fargo, North Dakota. (BL)

GROWING PLANTS WITHOUT SOIL FOR EXPERIMENTAL USE

Miscellaneous Publication No. 1251

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Contents

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GROWING PLANTS WITHOUT SOIL FOR EXPERIMENTAL USE

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Crop plants have been grown in soil for centuries. With the discovery of the many chemical substances in the soil, methods were developed for growing plants without soil. They were grown in such media as cracked rock, vermiculite, and coarse sand—all inherently very low in essential plant nutrients. The nutrients were supplied dissolved in water. This allowed researchers to regulate the kinds and amounts of nutrients available to the plant. However, because of the adhesive properties of the supporting media and because they could not always be relied on as purely inert materials, it was often necessary to use hydroponics or nutrient solution culture.

The original technique of growing plants hydroponically (*11*) [1] is still widely used (*7*) and has proved satisfactory in many instances. Many plants can be grown from seed to seed without ever coming in contact with soil. Some of the techniques used to grow plants without soil are described in detail (*5, 7, 8, 9, 12*). For a historical sketch of the development of the water culture method, see references *8, 9,* and *11*.

Plants grown in soilless culture have the advantage of a consistent supply of moisture and nutrients, resulting in steady growth (*2*). However, plants grown in solution culture may require more intensive care than those grown in soil to insure adequate moisture and to prevent development of nutrient toxicity or deficiency symptoms.

Much of the current research in experimental plant biology requires highly uniform plants. This quality of plant material is best grown under conditions in which the environment is carefully manipulated. Some research groups have centered their efforts on determining the environmental conditions under which maximum plant growth is achieved, with a view toward understanding the factors that limit plant growth, determining maximum growth rates, and exploring the potential for economical production of plants under controlled conditions.

In contrast, our objective has been to produce vigorous, healthy, uniform plant material in regulated environments for experimental purposes.

This publication is intended for those with some knowledge of plants who want to grow one or more species for experimental purposes, for demonstrations in schools, or for science projects where limited facilities are available. Techniques and equipment are described that are used at the Metabolism and Radiation Research Laboratory, Fargo, N. Dak., to raise crop and weed species in the absence of soil for experiments in which pesticides and their metabolites are applied to plants or plant parts, often in radioactive form. Some of the techniques have been adapted specifically for use with radioactive tracers, where consideration must be given to the absorptive properties of the containers and their disposability or ease of decontamination.

The growth procedures described here can be modified considerably to meet the facilities and budget of others who attempt to use them. The equipment is described here in some detail, but this degree of sophistication is not essential for growing plants, even for experimental purposes. The ingenious experimenter may have to modify the described techniques for his particular situation. For example, instead of a growth chamber, a converted room or part of a laboratory may suffice. We use vermiculite in many instances, but other inert supports such as "Jiffy Mix" may have to be

[1] Italic numbers in parentheses refer to Literature Cited, p. 16.

used, and commercially available fertilizers may have to be substituted for the pure reagents we use. This is entirely dependent on the purpose for which the plants are grown.

The growth conditions described here for each species will produce vigorous plants and can serve as guidelines. Deviations from these conditions can be used, but one must expect some variation in plant development. Generally this variation will not be of concern, particularly if the plants are to be used for demonstration and not for critical experiments.

CONTROL OF ENVIRONMENT

Since there are only four frost-free months in a year at Fargo, facilities to control the environment are required in order to grow plants throughout the year. We use greenhouses and controlled environment chambers for this purpose to duplicate growth conditions at different times.

Greenhouses

Many types of greenhouses are available. Commercially they vary considerably in size, shape, and construction materials (*15*). The covering may be glass or translucent plastic. Glass is more transparent, but it is susceptible to breakage and increases heat retention. Regardless of the type of greenhouse available, certain features are necessary to insure its usefulness for growing plants throughout the year. Provision must be made for winter heating, and some type of supplemental lighting is often needed during the winter. Necessary cooling is usually provided in the summer by a combination of some type of shading, cooling, and appropriate ventilation.

Temperature is controlled in the winter by thermostatically actuated steam heat. In mild climates proportional heat control may be desirable, but it is not necessary under severe winter conditions where greenhouse heat losses are high. The radiators are located around the perimeter of the greenhouse where they are most effective.

Shading of greenhouses in the summer is essential to prevent excessive heat buildup. It is generally accomplished either by painting the houses with a lime-linseed oil shading compound or by using a shade screen. One of the types available may be obtained from the Chicopee Manufacturing Co., Lumite Division, Cornelia, Ga. Shade screen can be installed on rollers near the greenhouse ridge and raised or lowered as needed. Although shade screen may be expensive to install initially, it will last for 6 to 10 years. In contrast, a shading compound has to be applied each spring and removed by scrubbing each fall. These operations require considerable labor if the greenhouse area is extensive. In addition, the shading compound will weather during the summer, often providing inadequate shading during the last part of the summer, and over the years it will etch the glass and thus reduce the transparency of the greenhouse during the winter.

Temperature is further controlled by using ridge or side vents, which may be hand or electrically operated. These vents are often used in conjunction with forced-air evaporative coolers, which bring air into the greenhouse. A high degree of summer temperature control can be achieved if both the evaporative coolers and motorized vents are thermostatically activated. The covering of vent openings with a fine screen such as Nitex 263, available from Smico Sales Co., Minneapolis, Minn., will exclude birds and most insects and thereby reduce plant damage and the need to fumigate more frequently for insect control.

The temperature in the greenhouse during the summer fluctuates between 21° and 35° C. During the rest of the year one of the sections of the greenhouse is kept at approximately 21° and the other sections at 27° during the day. Temperature is decreased about 6° in all sections at night. This provides a selection of temperature regimes for growing different types of plants.

Supplementary light controlled by timeclocks is best supplied by fluorescent lamps without reflectors. These provide minimum shading of the plant benches when the sun is shining and can be left in place permanently. We commonly use four 244-cm. fluorescent lamps (F96T12/CW 1,500 ma.) over each 122- by 244-cm. table. They supply from 300 to 600 foot-candles (ft.-c.) of illumination, which controls day length and is sufficient to maintain many species above the compensation point during the winter. These lamps have an average life of approximately 7,500 hours and can be used in the greenhouse for at least two win-

ters. Since they primarily supplement natural daylight in the greenhouse, we employ old lamps that have been used in growth-chamber illumination.

With an overcast sky during the day the natural illumination in the greenhouse is 900 to 1,100 ft.-c., and on a bright day it may reach 5,000 to 7,000 ft.-c.

The ideal situation is to grow each species of plant under the specific conditions in which it grows best. However, each species has requirements different from the next. Because of limitations in cost, space, and time, it is necessary at the Fargo laboratory to grow several species in the same greenhouse section or growth chamber. Therefore compromises have to be worked out. For example, peas [2] and barley may have to be grown next to each other. Peas grow best with cool temperatures and short days, whereas barley requires higher temperatures and longer days. When these two crops are grown side by side year around, we expect that neither will respond optimally to a compromise growth condition. The plants look healthy under these compromise conditions even though better growth could be obtained. We make every attempt to grow plants together that have similar growth requirements. For example, only if absolutely necessary do we attempt to grow peas and corn under the same conditions.

Under varying environments the water and nutritional requirements of plants will differ. During the summer it may be necessary to water the plants twice daily, whereas once a day may be satisfactory in the winter. The same is true when nutrient solution is applied two or three times a week, alternating with water only. If the growth rate of the plants increases, additional nutrients are necessary. A decreased growth rate is accompanied by reduced nutrient requirements. As the plants approach maturity, their nutrient requirements gradually decrease.

For certain species of plants, the flowering stage may be delayed or hastened according to the photoperiod they receive (*4*). The growth rates of the plants discussed here and that are listed in table 2 were obtained under average conditions in the greenhouse. The photoperiods, light intensities, temperatures, and humidities listed in tables 2 and 3 are those found to be satisfactory in growth chambers or incubators.

[2] For scientific names, see the index.

Growth Chambers

Many types of controlled environment systems for raising plants are available commercially and their use in research is increasing. The systems vary considerably in size and capability, ranging from simple lighted cabinets to those providing rigorous control of several environmental parameters. Growth chambers are used primarily (1) to obtain uniform plant material, (2) to permit selection of environmental conditions appropriate for a given plant species without regard to season, and (3) to permit environmental manipulation as an experimental variable. If more than one type of growth chamber is available, the selection of the most appropriate one will depend on its intended use.

In general, all growth chambers contain mechanical, electrical, and perhaps electronic components and controls, all of which are subject to breakdown and require maintenance. The more sophisticated chambers generally provide greater flexibility of operation but often require more frequent or more complicated maintenance. Usually the simplest chamber that will meet the required environmental conditions is the best and often the least expensive.

Several kinds of growth chambers are used for different types of experiments at the Fargo laboratory. Since all the environmental factors are interrelated in their effect on plant growth (*10*, *16*), none can be considered independently of the others. However, satisfactory control of a few major parameters will result in uniform and reproducible plant growth.

Temperature control is usually achieved through the combined use of refrigeration and heating systems that are thermostatically controlled. It is most useful to have two thermostats, one to control day temperature and the other for night temperature, with a timeclock to switch from one to the other. Switching need not coincide with the light-dark cycle. Temperature control of ±2.0° C. is adequate for many purposes. Continuous temperature programing is provided in some growth chambers, but it is not needed for most experimental work. The degree of temperature control provided in an ordinary laboratory or classroom may be adequate for many purposes, and the on-off cycling of

adequately ventilated banks of lights will provide some day-night temperature differential.

The lighting for growth chambers is commonly provided by a combination of fluorescent and incandescent illumination, banks of which commonly occupy the entire ceiling. The quality of the light from artificial lamps is not equal to sunlight (*14*). However, a satisfactory light quality may be achieved by using approximately 4 watts of cool-white fluorescent illumination per watt of incandescent illumination. The incandescent lamps need not be larger than 60 watts, although 100-watt lamps are sometimes used.

Control of day length is an essential part of environmental regulation. Timeclocks that can be set to turn the lights on or off at any 15-minute interval are satisfactory for most purposes. Regulation of light intensity is most commonly achieved by a combination of varying the distance between the plant bed and the light bank and by varying the number of lamps lighted at any given time. Most growth chambers contain a mechanism for adjusting the plant bed height and several timeclocks, each controlling a part of the lights. Although illumination as low as 400 ft.-c. may be desirable for some purposes, most plants will grow satisfactorily in a white-walled chamber under a measured illumination of 1,000 to 2,500 ft.-c.

Many growth chambers can provide illumination considerably in excess of 2,500 ft.-c.; however, the literature reveals that 1,600 to 2,000 ft.-c. is usually sufficient for vigorous growth. Achieving maximum growth rates may require higher illumination.

The lamp bank and associated electrical ballasts generate a considerable amount of heat and this must be dissipated if temperature control is to be achieved. One of the better growth-chamber arrangements has the ballasts in a compartment insulated from the plant growth space and the lamp bank itself isolated from the plant growth space by a transparent barrier. If open lamp banks are used in a laboratory or classroom, adequate ventilation must be provided to prevent excessive heat buildup on the plant bed and in the room itself.

Some degree of humidity control is commonly provided in many growth chambers. Such chambers have a humidity sensing apparatus, which controls the operation of a refrigeration coil to trap unwanted water vapor, and a steam generator, wet pad, or aerosal generator to increase moisture in the air. In closed growth chambers without humidity control, precautions must be taken to insure adequate ventilation and thereby prevent the excessive moisture buildup that results from transpirational water loss from plants held in an enclosed space. Increased humidity may promote mildew development. If plants are grown under a light bank in a laboratory or classroom, humidity control is not practical and normal watering of the plants should be sufficient. A fresh-air change every 2 hours in the chamber is desirable to prevent excessive carbon dioxide buildup at night and a depletion during the day.

Since there is so much variety in growth chambers depending on the manufacturer and on the purpose of the chamber, the reader is referred to manuals and specifications of the manufacturers. Anyone planning to purchase new chambers should consult with those who have had practical experience with several types.

Seed Germinators

At the Fargo laboratory a temperature-controlled incubator is used for seed germination. Most seeds are germinated in the dark, although some require light. If a dark incubator is not available, any dark cabinet in which the temperature remains fairly constant between 21° and 27° C. can be used, and reasonably uniform and reproducible seed germination of the species listed here (p. 17) will occur. Other species having special germination requirements occasionally may be encountered.

IMPORTANT FACTORS FOR PLANT GROWTH

Illumination and quality of light, photoperiod, temperature, relative humidity, and nutrition all interact to affect plant growth. If any one of these factors is less than optimum, poor plant growth can result (*4, 5, 14*).

Good plant growth usually can be obtained

by selecting environmental conditions approximating those under which the plant flourishes in nature. Once established, species from arid regions often grow well under dry conditions and those from nonarid regions often grow well under humid conditions. When the environment can be controlled at least partially, these conditions can often be met and the results are usually gratifying.

Because there are so many different species and varieties of plants with differing needs for optimum growth, the grower should experiment to find the optimum conditions for each species or variety.

Light

Light is required for plant growth. The illumination, light quality, and photoperiod requirements vary among species (*14*). A number of different instruments may be used to measure illumination. In biological research a foot-candle meter is often used to measure illumination. The illumination on a surface that is everywhere 1 foot from a uniform point source of light of one candle intensity is equal to 1 lumen per square foot or 1 ft.-c. Although inexpensive foot-candle meters can be obtained, photographic light meters are more generally available and are practical for light measurement. Photographic light-meter readings can be converted to foot-candles by the following formula:[3]

$$B = \frac{20(f)^2}{TS}$$

Where

B = illumination in foot-candles
f = aperture in f stop
T = shutter speed in seconds
S = film speed in ASA units

To measure illumination with a photographic light meter, reflected rather than incident light must be measured. To do this, place a large sheet of white paper on the surface to be measured, set an appropriate ASA film speed on the meter, and read the shutter speed required for proper exposure at a given f stop. Values for ASA speeds of 64 to 100 at various f stops and shutter speeds are given in table 1. Values for other meter settings may be obtained by solving the equation. The results will be approximate depending on the accuracy of the meter and the cone of light it accepts. For example, false low readings may result if the meter accepts light from an area greater than that of the white paper at which it is directed. Nevertheless the readings can suffice to determine whether illumination is adequate for good plant growth. About 1,200 ft.-c. of light in a growth chamber is satisfactory for many plants such as cabbage, carrots, peas, and tobacco, whereas other plants such as corn, cotton, rice, and sorghum grow better when supplied with 1,600 to 1,800 ft.-c.

TABLE 1.—*Relationship between photographic light meter readings and foot-candles* [1]

Film speed (ASA)	Aperture	Shutter speed	Illumination
	F stop	*Seconds*	*Ft.-c.*
100	16	1/2	102
64	16	1/2	160
100	16	1/5	256
100	11	1/15	363
64	16	1/5	400
100	16	1/10	512
100	11	1/25	605
100	16	1/15	768
64	16	1/10	800
100	16	1/20	1,024
64	16	1/15	1,200
100	16	1/25	1,280
100	11	1/60	1,452
64	16	1/20	1,600
64	16	1/25	2,000
100	16	1/50	2,560
100	16	1/60	3,072
100	11	1/150	3,630
64	16	1/50	4,000
64	16	1/60	4,800
100	16	1/100	5,120
100	16	1/125	6,400
64	16	1/100	8,000
64	16	1/125	10,000
100	16	1/200	10,240

[1] Measure light reflected from a white paper or other similarly textured surface.

[3] We are indebted to John A. Witz, Department of Electrical Engineering, Oklahoma State University, Stillwater, for supplying this formula.

The quality or spectral composition of light affects the growth and development of plants (*4*). An improper balance of light quality can result in abnormal growth.

Different plant species vary in their photoperiod requirements for best growth. For example, barley requires a photoperiod greater than 12 hours for good flowering, whereas soybeans can mature under a 12-hour day. The photoperiod can be regulated to hasten or delay flowering (*4*). In the growth chambers the plants can be given whatever photoperiod is required for optimum plant growth. Some suggested photoperiods are given in table 2.

In the greenhouse many different species of plants are grown. Some of these may require long days for flowering and others short days. It is impossible to provide the optimum light requirements for each species, but many plants can be grown satisfactorily. During the winter a 12-hour photoperiod is generally used as a compromise day length under which reasonable vegetative growth can be maintained. The short natural photoperiod in the winter is supplemented with fluorescent light.

Temperature

During the summer it is often difficult to maintain cool enough temperatures in the greenhouses for certain species of plants. For example, head lettuce and peas will often grow poorly in midsummer. It is not recommended to grow these species until conditions are more favorable.

Relative Humidity

When moisture supply to the roots is adequate, the degree of water vapor saturation in the air exerts a major effect on the rate of transpiration of many plants. An average of 50-percent relative humidity is satisfactory for many species.

A relative humidity of 100 percent is often needed to germinate very small seeds such as those of tobacco or bluegrass or to root sugarcane stem sections. The required humidity can be obtained by covering the plant containers with plastic bags. If mildew infection is a problem under high humidity, a light dusting with sulfur may be sufficient to control it.

Growth Media

At the Fargo laboratory the plants are not grown in soil but in either vermiculite or deionized water. Vermiculite of a medium fine texture, sometimes called horticultural grade, is readily obtained from local dealers. Local tapwater may be too saline or alkaline for use in nutrient culture. It is usually deionized by passage through a commercial mixed-bed deionizer. The resins remove cations and anions such as potassium and chloride ions from the tapwater.

Nutrition

Environmental conditions affect the amount and rate of nutrient uptake by individual plants. If many different kinds of plants are to be grown, considerable variation in nutrient requirements can be expected. By careful observation, early deficiency or toxicity symptoms can be diagnosed and readily cured (*2*, *13*). If fairly exact nutrient requirements are not known for a given species, it is best to use a standard solution, such as those given on pages 13 and 14, taking care not to overfertilize, for it is easier to correct a nutrient deficiency than a toxicity. Many plants seem to tolerate wide variations in nutrient supply. It is naturally desirable to supply nutrients at the optimum level.

Nutritional guidelines for several species are listed in table 3. These have proved very satisfactory at the Fargo laboratory. One should not expect that these methods are optimum for other growth conditions, and some alterations may be required. In this respect nothing replaces common sense, careful observation, and a little "tender, loving care."

In the Fargo laboratory we use a modification of one basic nutrient solution (*9*), in which a chelated form of iron is substituted for the iron salt originally reported. This is satisfactory for most of the plants. The full-strength solution is made up and the concentration varied simply by diluting to three-fourths, one-half, or one-third strength with deionized water. Tapwater may be substituted for deionized water in some localities. We find that generally the full-strength solution is too concentrated for many species, particularly in early stages of growth.

TABLE 2.—*Light, temperature, and humidity requirements and development of selected plants* [1]

Species [2]	Conditions used in growth chambers				Plant development under average greenhouse conditions			
	Illumination	Photoperiod	Temperature (day-night)	Humidity	Height in—		Bloom	Maturity
					4 weeks	8 weeks		
	Ft.-c.	*Hours*	*° C.*	*Percent*	*Cm.*	*Cm.*	*Days*	*Days*
Alfalfa	1,500	14	26-20	40	20	36	76	100
Barley	1,600	16	30-20	40	25	61	60	90
Barnyardgrass	2,200	14	30-25	50	30	55	50	70
Bean 'Black Valentine'	1,500	12	20-15	60	36	--	30	[3] 65
Beet	1,200	12	25-20	50	--	30	--	120
Bermudagrass	1,200	12	26-20	50	8	15	75	90
Bluegrass	1,200	12	26-20	40	8	20	75	90
Broadbean	1,200	14	20-10	50	30	70	45	85
Broccoli	1,400	12	23-18	55	20	36	--	[4] 120
Buckwheat	1,400	12	26-20	50	15	55	35	70
Cabbage	1,400	12	23-18	55	15	36	--	[4] 120
Carrot	1,200	12	23-15	50	10	30	--	85
Corn	1,600	14	30-25	70	76	183	56	105
Cotton	1,800	14	30-25	40	20	51	50	90
Cucumber	1,400	14	30-23	50	--	--	35	60
Dill	1,200	12	30-23	55	15	81	60	100
Endive	1,200	12	23-16	60	10	--	--	[4] 70
Fall panicum	1,200	12	23-16	40	15	--	40	70
Flax	1,400	12	30-20	50	20	61	45	85
Head lettuce	1,600	14	23-16	60	12	--	--	70
Johnsongrass	1,600	14	30-23	60	122	--	40	--
Leaf lettuce	1,600	14	25-18	60	--	--	--	60
Limabean	1,500	12	20-15	40	30	--	40	75
Melon	1,400	14	30-23	50	--	--	35	60
Millet	1,800	14	30-23	40	20	86	60	100
Mustard	1,400	12	23-18	55	15	50	60	--
Oat	1,600	16	30-20	40	25	70	70	100
Okra	1,500	14	30-20	50	30	61	50	80
Parsnip	1,200	12	23-15	50	36	--	30	60
Pea	1,200	12	20-15	50	36	--	30	60
Peanut	1,600	14	30-25	40	15	36	42	100
Pepper	1,400	14	30-20	50	--	30	60	85
Pigeongrass	2,200	14	30-25	50	25	--	40	65
Pintobean	1,500	12	20-15	60	36	--	30	65
Plantain	1,200	12	25-20	40	--	15	70	90
Potato	1,400	12	21-16	40	15	61	50	75
Red clover	1,200	12	21-16	50	--	20	80	110
Rice	1,600	14	30-25	70	30	76	75	105
Sorghum	1,800	14	30-23	40	20	86	60	100
Soybean	1,600	12	30-20	40	36	56	35	80
Spinach	1,400	12	25-20	55	--	25	50	--
Squash	1,400	14	30-23	40	--	--	35	60
Sudangrass	1,800	14	30-23	40	20	86	60	100
Sugarbeet	1,200	12	25-20	50	10	36	--	120
Sugarcane	1,800	14	30-25	50	8	38	--	140
Sunflower	1,600	14	30-25	30	76	178	56	100
Sweetpotato	1,400	12	25-20	50	15	--	--	85
Swiss chard	1,400	12	25-20	60	10	30	--	--

See footnotes at end of table.

TABLE 2.—*Light, temperature, and humidity requirements and development of selected plants* [1]—Continued

Species [2]	Conditions used in growth chambers				Plant development under average greenhouse conditions			
	Illumination	Photoperiod	Temperature (day-night)	Humidity	Height in— 4 weeks	Height in— 8 weeks	Bloom	Maturity
	Ft.-c.	*Hours*	*° C.*	*Percent*	*Cm.*	*Cm.*	*Days*	*Days*
Tobacco	1,200	14	30-25	60	1	10	120	140
Tomato	1,400	14	25-25	50	20	61	50	100
Turnip	1,200	12	25-20	60	10	35	..	65
Wheat	1,600	16	30-20	40	25	61	70	100
Wild buckwheat	1,200	12	25-20	50	30	..	50	65
Wild mustard	1,400	12	23-18	55	30	..	28	60
Wild oat	1,600	16	30-20	40	25	70	60	90

[1] Plant development is similar for a given species whether raised under growth-chamber conditions listed or average greenhouse conditions.

[2] See index for scientific names.

[3] Edible pods in 45 days.

[4] Harvested heads.

GERMINATION OF SEED

The plants described here are primarily crop species and their seeds are easy to germinate. However, problems do exist with seed germination of certain plant species. An extensive text on plant propagation (*6*) has been published and should be very useful if problems are encountered. The germination methods used in the Fargo laboratory will be discussed here. Additional comprehensive information on seed germination has been published by Andersen (*1*) and Barton (*3*).

Method 1

A small flat, 30 by 20 by 10 cm., is filled with 5 cm. of vermiculite. The seed is placed on top of the vermiculite and covered with 1.3 cm. of vermiculite for such seeds as alfalfa and 2.5 cm. for pea seeds. Very small seeds such as those of tobacco are mixed with sand to increase the volume for better distribution. These seeds are not covered after seeding. The vermiculite is wetted from the bottom. An enamel tray is placed under the flat to maintain the moisture level. The flat with tray is placed in an incubator at the desired temperature for the required length of time. If the seedlings are kept in the flat for an extended period of time, a dilute nutrient solution can be used in place of water. Metal flats should be of stainless steel, or if galvanized they should be coated with an asphaltic material to prevent toxic levels of zinc from leaching into the germinating medium.

This method is generally the easiest and most successful for many types of seeds. The advantages of using vermiculite for germinating seed are as follows: (1) It has adequate moisture-holding capacity and aeration. (2) It contains virtually no nutrients or toxic materials. (3) Roots develop well in it. (4) It is light weight and easy to handle. Although peat may be mixed with verimiculite for some purposes, its high absorptivity may interfere with subsequent chemical treatments applied to the roots.

Method 2

Two pieces of absorbent paper toweling approximately 20 by 30 cm. are wetted thoroughly and laid on a sheet of waxed paper of the same size. The upper paper is folded back 5 cm., seed is placed on the second paper along the fold, and the upper paper is folded back over the seeds again. The absorbent papers are rolled loosely

TABLE 3.—*Germination, transplanting, and nutrient requirements for selected plants*

Species [1]	Germination				Period between seeding in vermiculite and—		
	Method [2]	Seeding depth	Temperature	Time	Transplanting in nutrient solution	Applying nutrient solution at—	
						One-third strength	One-half strength
		Cm.	*° C.*	*Days*	*Days*	*Days*	*Days*
Alfalfa	1	1.3	26	6	--	6	--
Barley	1, 2	2.5	30	6	--	6	21
Barnyardgrass	1	1.3	30	6	14	6	--
Bean 'Black Valentine'	1, 2	2.5	27	6	--	--	6
Beet	1	2.5	25	7	21	7	21
Bermudagrass	1	0	26	7	21	7	--
Bluegrass	1	0	26	7	21	7	--
Broadbean	1, 2	3.8	24	10	--	10	--
Broccoli	1	1.3	23	6	21	6	21
Buckwheat	1, 2	2.5	30	5	--	5	--
Cabbage	1	1.3	23	6	21	6	15
Carrot	1	1.3	23	7	28	7	--
Corn	1, 2	2.5	30	5	--	5	21
Cotton	1, 2	2.5	30	5	--	0	21
Cucumber	1, 2	2.5	30	5	--	5	21
Dill	1	1.3	30	7	28	7	28
Endive	1	1.3	23	5	28	5	--
Fall panicum	1	2.5	23	8	21	8	--
Flax	1	1.3	30	4	21	4	--
Head lettuce	1	1.3	23	5	14	5	--
Johnsongrass	1	[3] 5.0	30	7	--	--	7
Leaf lettuce	1	1.3	25	5	14	5	--
Limabean	1, 2	2.5	27	6	--	--	6
Melon	1, 2	2.5	30	5	--	5	21
Millet	1, 2	1.3	30	5	14	5	14
Mustard	1	1.3	23	6	21	6	21
Oat	1, 2	2.5	30	6	--	6	21
Okra	1, 2	2.5	30	5	--	5	--
Parsnip	1	1.3	23	10	28	10	--
Pea	1, 2	2.5	24	5	--	--	5
Peanut	1, 2	3.8	30	7	--	7	42
Pepper	1	1.3	30	10	28	10	--
Pigeongrass	1	1.3	30	6	14	6	--
Pintobean	1, 2	2.5	27	6	--	--	6
Plantain	1	0	25	7	49	7	--
Potato	1	[3] 5.0	21	[3] 10	--	10	--
Red clover	1	1.3	21	6	28	6	--
Rice	1, 2	2.5	30	7	--	7	--
Sorghum	1, 2	1.3	30	5	14	5	14
Soybean	1, 2	2.5	30	5	--	5	--
Spinach	1	1.3	25	5	28	5	--
Squash	1, 2	2.5	30	5	--	5	21
Sudangrass	1, 2	1.3	30	5	14	5	14
Sugarbeet	1	2.5	25	7	21	7	21
Sugarcane	1	1.9	30	7	35	7	35
Sunflower	1, 2	2.5	30	4	--	4	28

See footnotes at end of table.

TABLE 3.—*Germination, transplanting, and nutrient requirements for selected plants*—Continued

Species [1]	Germination				Period between seeding in vermiculite and—		
	Method [2]	Seeding depth	Temperature	Time	Transplanting in nutrient solution	Applying nutrient solution at—	
						One-third strength	One-half strength
		Cm.	*° C.*	*Days*	*Days*	*Days*	*Days*
Sweetpotato	1	[4]2.5	25	[5]14	--	14	--
Swiss chard	1	2.5	25	6	--	6	--
Tobacco	1	0	30	7	40	7	60
Tomato	1	1.3	25	7	21	7	21
Turnip	1	2.5	25	4	21	4	--
Wheat	1, 2	2.5	30	6	--	6	21
Wild buckwheat	1	2.5	25	10	--	10	--
Wild mustard	1	1.3	23	6	21	6	21
Wild oat	1, 2	2.5	30	6	--	6	21

[1] See index for scientific names.
[2] Method 1 = vermiculite; method 2 = paper roll (see pp. 8–11).
[3] Rhizome sections.
[4] Tuber or fleshy root.
[5] Shoot emergence from tuber or fleshy root.

inside the waxed paper, placed in a beaker or jar with 5 cm. of water, and incubated at the desired temperature, usually in the dark (fig. 1). The absorbent paper keeps the seeds moist and the waxed paper prevents the toweling from drying out. Generally 4 to 5 days' incubation is required.

When the seedlings are removed from a dark incubator, they are colorless or etiolated and cannot be exposed to bright illumination without first hardening them for a day in room light (100–200 ft.-c.). If the seedlings are directly exposed to sunlight or bright illumination in a growth chamber, the hypocotyl or cotyledons may be damaged and the seedlings may die. For example, it has been our experience that unhardened soybean seedlings become scalded if transferred directly from a dark incubator into a growth chamber with an illumination of 1,600 ft.-c. In contrast, hardened seedlings can be transplanted and placed in an environment with any required illumination.

Seed germination by the "paper roll" method may require more time and care than direct seeding in flats. However, distinct advantages make the method worthwhile. Seedlings germinated by the paper roll method may be selected for uniformity of root and shoot development and may be transferred to nutrient or other solutions with minimum root damage and without particulate matter adhering to them.

PN-2923

FIGURE 1.—Germination of cucumber seed on moist paper toweling.

Some precautions to be taken when using paper rolls are as follows: (1) If the seed is too small, the wet paper toweling will seal off the oxygen supply and cause poor germination. (2) Seed may mold if spores are present unless treated with a mild fungicide, or the rolls can be checked after 48 hours and the bad seeds removed. (3) Chemicals toxic to certain seeds might be present in the paper and inhibit growth.

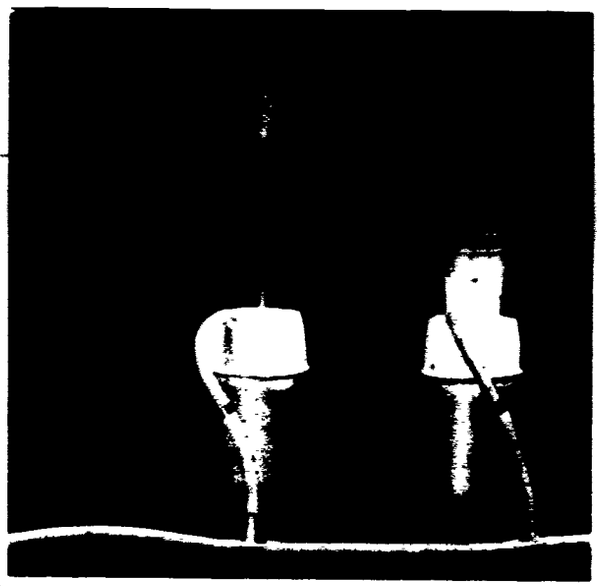
TRANSPLANTING

When seedlings have been germinated in a paper roll, they can be transplanted easily into nutrient troughs (fig. 2) or individual solution containers (fig. 3).

When plants are uprooted from vermiculite or soil, some root damage may occur. The plant will continue to transpire and may wilt if little moisture can be absorbed by the damaged roots. Wilting can be minimized by reducing transpiration. This can be accomplished by keeping the plant moist, lowering the temperature, and diminishing the airflow around the plants. When uprooted plants are handled in this manner, they can be kept without harm for 12 to 24 hours until transplanted. Exposing plants to direct sunlight and high temperature immediately after transplanting causes an enormous stress on them. They should be kept at 15° to 21° C. for 48 hours to slow the transpiration rate and to prevent wilting.

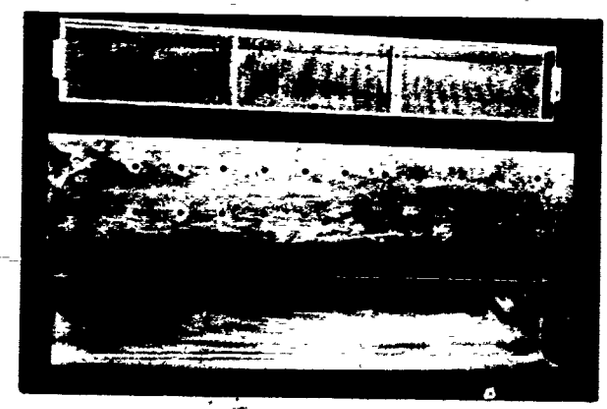
The size, age, and type of plant being transplanted often determine success or failure. In general, younger plants are more successfully transplanted. Selection of uniform seedlings is essential to obtain uniform subsequent growth. The roots should be inserted vertically into the solution or vermiculite without bending or leaving them exposed. A little extra care at the time of transplanting will give improved results throughout the growing season. The transplanting medium such as soil or vermiculite should be saturated with water or dilute nutrient solution to restore the moisture that the plant may have lost. Care must be taken not to have the nutrient solution too concentrated when transplanting directly into it, or salt injury and desiccation may occur. It is advisable to increase the concentration of the nutrient solution gradually as the plant grows. If seedlings are transplanted to containers of vermiculite 30 cm. or more in diameter, some of the nutrient salts are adsorbed on the vermiculite and are not available to the plant. This can be avoided by using a slightly stronger nutrient concentration.

If transplanting into specialized containers is not required, seed may be planted directly into pots with vermiculite and grown in that manner.



PN-2925

FIGURE 3.—Corn and pea seedlings growing in aerated nutrient solution, with capillary tubing (0.25 mm.) inserted into air line for each culture jar.



PN-2924

FIGURE 2.—Nutrient culture trough: Plastic frame insert with nylon screen bottom, metal cover, and stainless-steel trough with drain (top to bottom).

CULTURE TECHNIQUES

Containers

The plant container must be of sufficient size to permit adequate root growth; otherwise the development of the plant may be restricted. For example, a pea plant can be grown to maturity in a 10-cm. plastic pot filled with vermiculite or in a 500-ml. jar filled with nutrient solution. A corn plant grown in a 10-cm. pot or 500-ml. jar becomes rootbound after 5 to 6 weeks of growth and abnormalities will occur. Corn plants require an 18-cm. pot or 2-liter jar to grow to maturity. For this reason various types and sizes of containers are used, such as jars, stainless-steel troughs with lids, and plastic pots with saucers. Milk cartons can also be used as disposable containers. They will often last for 6 to 8 weeks. Glass jars are covered with a coat of black paint followed by a coat of aluminum paint. The black paint excludes light, inhibits growth of algae in the nutrient solution, and prevents abnormal root pigmentation. Since the aluminum paint reflects sunlight, the jars remain cool.

When many plants are to be grown together in the same container in nutrient solution for experimental purposes, we use a stainless-steel trough, 66 by 15 by 10 cm., with a stainless-steel lid (fig. 2). The plants are placed in holes in the lid, which serves as a support and keeps out the light. Soft plastic collars may be used for additional stem support. The size of the holes should be adequate to prevent stem girdling. Alternatively the flat steel trough lids may be replaced by wood or plastic frames with nylon screen bottoms. These frames are supported within the troughs, 3.8 cm. above the bottom (fig. 2). The screen is filled with vermiculite. The plants can be grown directly from seed or transplanted. Nutrient solution is added to wet the vermiculite. The plant roots grow through the screen and into the nutrient solution. Many plants grow well in this manner. The screen gives good root support, and most of the roots can be harvested.

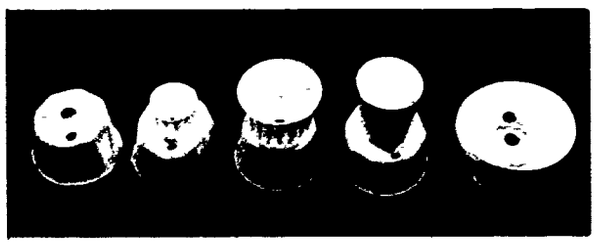
Plexiglas framing is preferred to wood to avoid leaching of chemicals from the frame. If in an experiment it is necessary to treat the roots by adding a chemical to the nutrient solution, a wooden frame might become contaminated and should be discarded.

When plants are grown in jars, the jar lids, tinfoil, waxed cork, Masonite, or other materials can be used for plant support. However, we have found paper cups most satisfactory for support. They can be used in different ways depending on the species of plant to be grown. For example, when pea plants are grown, two cups are glued together on the bottom (fig. 4). The lower cup slips over the outside of the jar; the upper cup is used for plant support. One small hole is punched through the bottom of each cup for the seedling and another small hole through the lower cup for the aeration tube.

Reasons for using this technique are as follows: (1) The cups are chemically unreactive. (2) They are cheap enough to be discarded after a single use. (3) Sharp cutting edges are eliminated that may injure the hypocotyl, stem, or roots. (4) Girdling can be prevented by gradually enlarging the hole as the plant stem increases in diameter. (5) Cups can be easily lifted so that nutrient solution can be added. (6) Plants can be easily transferred to other jars. (7) There is more stem support for certain plants than with many other types of lids.

Aeration

When plants are grown directly in liquid culture, air usually must be supplied to the nutrient solution. A small electric pump such as a fish tank aerator can force air through rubber or plastic tubing to the jar or troughs. Glass capillary tubing is inserted in the solution. A well-regulated uniform flow rate can be obtained for several aerators on the same line by inserting a 2.5-cm.



PN-2926

FIGURE 4.—Paper cups and lid supports for plants grown in culture jars.

length of 0.25-mm. bore capillary tubing into the air line for each aerator tube (fig. 3). Aerating can be done continuously or at regular intervals, such as 2 hours on, 2 hours off, by using a time-clock.

If compressed air is available, this may be more economical than using many small pumps, which require frequent maintenance. Oil vapors from a rotary-type compressor must be trapped out with a charcoal filter before the air reaches the plants.

Subirrigation

At the Fargo laboratory the plants grown in vermiculite-filled pots or flats generally receive water and nutrient solution by subirrigation. Saucers or shallow pans are used under the pots and enamel trays under the flats. The amount of water or nutrient solution added is dependent on the plant and growing conditions. Common sense and experience are often required to determine how often and how much to water. It is not so easy to overwater plants grown in vermiculite as it is in soil. However, plants that require well-aerated media can become waterlogged if the vermiculite is watered excessively. Care must be taken to avoid this. Waterlogged plants will often wilt, although for different reasons than when they are desiccated. When in doubt, consult those who have previously grown these plants, or refer to literature on the specific plant (*2*).

Some salt accumulation may occur on the surface of the vermiculite after a period of time, and this should be leached out once a month. This is done by applying excess water at the top and letting it drain through the container. Then subirrigation can be resumed on the usual schedule. Salts are leached away very rapidly from vermiculite by this method (*2*). The pots and flats are watered from the top only at seeding time. When very small seed is placed in flats and left uncovered, subirrigation is used. If they are watered from the top, a fine spray must be used to prevent the seed from being carried too deep into the vermiculite to emerge.

The following methods can be used to apply nutrients to plants: (1) Mix the nutrients directly into the watering system. (2) Add nutrient solution two or three times per week and water at other times. (3) Supply a nutrient solution every day without mixing it in the watering system; the concentration can then be varied as needed. When using method 2, tapwater can often be substituted for distilled or deionized water if the plants are not going to be used for a critical experiment in which nutrition should be carefully controlled. The use of tapwater several times per week has the advantage of reducing the volume of deionized water required. However, it must be employed with caution, since some domestic water supplies are apt to contain levels of salts that will damage plants. Soft water is not necessarily low in salt content since the softening process usually only exchanges highly soluble salts for less soluble ones.

The acidity or alkalinity of the water used may also affect plant growth adversely. Some of the adverse pH effects probably result from changes in the availability of nutrient salts. For example, excessive watering of corn with alkaline (pH 9) tapwater can cause the leaf margins to become chlorotic and torn. These symptoms are reminiscent of certain nutrient deficiencies! The addition of dilute acids, bases, or buffering salts to the tapwater or nutrient solution can help overcome these difficulties. Care must be taken, however, to insure that neither the nutrient solution nor the tapwater used between additions contains too much salt.

We emphasize again that it is necessary to experiment in order to determine the optimum amounts of nutrient for individual species.

Nutrient Solution

The formula of Hoagland and Arnon (*9*) is used with a slight modification. Preparation is as follows:

Preparation of Stock Solutions

Major Elements.—Individual 1 M stock solutions of each major element are made with deionized water.

Chemical	*Formula*	*Grams per liter*
Potassium dihydrogen phosphate	KH_2PO_4	131.1
Potassium nitrate	KNO_3	101.1
Calcium nitrate	$Ca(NO_3)_2 \cdot 4H_2O$	236.2
Magnesium sulfate	$MgSO_4 \cdot 7H_2O$	246.5

Iron Solution.—Chelates of iron in ethylenediamine tetraacetic acid are commercially available, often as Versene or Sequestrene. Dilute the commercial product to obtain a 5-percent w/v solution. Dissolve 200 ml. of this solution in distilled water and make to 1 liter. This stock solution contains 10,000 p.p.m. of iron. One ml. of stock solution will give an iron concentration of 10 p.p.m. when diluted to 1 liter.

Micronutrients.—The microelements or trace elements are dissolved together in 1 liter of deionized water to make a stock solution. The microelements should be added to the water in the order listed and each dissolved before the next is added. This prevents precipitates from forming.

Chemical	*Formula*	*Grams per liter*
Boric acid	H_3BO_3	2.50
Zinc chloride	$ZnCl_2$	.50
Cuprous chloride	$CuCl_2 \cdot H_2O$	.05
Molybdenum oxide	MoO_3	.05
Manganese chloride	$MnCl_2 \cdot 4H_2O$	.50

Preparation of Nutrient Solution From Stock Solutions

The following volumes of the six stock solutions are then individually added to about 500 ml. of deionized water with stirring. After all stock solutions have been added, the nutrient solution is made to 1 liter with deionized water to obtain a full-strength solution. This solution is usually diluted to one-third, one-half, or three-fourths strength.

Chemical	*Formula*	*Milliliters*
Potassium dihydrogen phosphate	KH_2PO_4	1
Potassium nitrate	KNO_3	5
Calcium nitrate	$Ca(NO_3)_2$	5
Magnesium sulfate	$MgSO_4$	2
Iron		1
Micronutrients		1

TECHNIQUES FOR SPECIFIC PLANTS

Tables 2 and 3 summarize the methods used for growing several plant species. In table 2 are listed the light, temperature, and humidity regimes used for these species when raised in growth chambers and also some growth characteristics obtained under average greenhouse conditions. These characteristics also closely approximate those obtained in growth chambers as listed for each species. In table 3 the germination method, germination period, and nutrient requirements are listed.

For many of the species additional precautions and comments are to be noted if good plant growth is to be insured. These species are listed alphabetically by common name. Some plants are grouped together since their specific growth requirements are nearly identical. For plants not in alphabetical order, see the index.

Alfalfa.—This species may be propagated vegetatively as well as from seed. Five-cm. stem sections, each bearing one or two trifoliate leaves near the apical end of the cutting, are removed from well-established plants and rooted in moist vermiculite or aerated water for 3 weeks. During this period a 12-hour photoperiod with an illumination of 1,000 ft.-c., day-night temperatures of 21° and 16° C., and a relative humidity of 75 percent can be used. Flowering can be induced by interrupting the dark cycle for 1 hour near the middle of the night or by increasing the illumination to about 2,200 ft.-c. 1 or 2 weeks after transplanting.

Barley, Oat, Wheat, and Wild Oat.—The barley variety 'Larker' is susceptible to mildew. This disease may be controlled by lightly dusting the plants with sulfur. It may be desirable to add potassium bicarbonate at a final concentration of 2×10^{-3} M to the nutrient solution to prevent leaf tipburn of 'Larker' barley. Other barley varieties may not require this treatment. To hasten maturity of barley, oat, wheat, and wild oat grown under short-day conditions, it is necessary to interrupt the dark period with light for 1 hour near midnight.

Barnyardgrass, Pigeongrass, and Rice.—When these species are grown in liquid culture, no aeration is required. These grasses may be transplanted directly into one-third strength solution

supplied continuously, or they may be directly seeded into vermiculite-filled screen frames (fig. 2) and moistened with one-third strength solution to obtain a dense stand.

Bean 'Black Valentine,' Broadbean, Limabean, and Pintobean.—These species have a wide nutritional tolerance. The first symptom of deficiency is a reduction in leaf area of newly expanding leaves that may be readily corrected before any leaf injury becomes apparent Pollination of broadbean flowers is best done by hand or by using an oscillating fan near the plants for a few hours each day. The relative humidity should be kept low for maturing limabeans to prevent seed from sprouting while still in the pod.

Beet and Sugarbeet.—If these species are to be raised in vermiculite without transplanting, they may be supplied with one-half strength solution at time of seeding.

Bermudagrass and Bluegrass.—Vegetative propagules of bermudagrass may be obtained from sections of runners. Freshly harvested bluegrass seeds are often dormant. Good germination of 2- to 4-year-old seed can be obtained by moistening with nutrient solution under high humidity. Once germinated, the seedlings should be grown under low humidity to prevent mildew infection. Bluegrass may be vegetatively propagated by subdividing the crowns.

Buckwheat.—This species requires hand or insect pollination to insure seed set.

Cabbage, Mustard, and Wild Mustard.—Some stem injury to cabbage may occur if young plants are not well supported in liquid cultures or if nutrient salts are allowed to accumulate on stems. Mustard grows better in vermiculite than in liquid culture. Wild mustard has low nutrient requirements and leaf burn may occur if solutions more concentrated than one-third strength are used. Mature plants are large enough to tip solution culture jars if they are not well supported.

Carrot.—Roots of this species are abnormally branched and short when grown in solution culture.

Corn.—This species is sensitive to nutritional changes during the first 4 to 6 weeks and requires a plentiful iron supply at all times. If grown in solution culture, best results are obtained when the solution pH is maintained near 7. Plants will be severely stunted if grown in 500-ml. containers. Two-liter solution containers or 18-cm. pots are recommended if corn is to be grown to maturity.

Cotton.—Seed should be moistened with one-half strength solution if started in vermiculite or with one-third strength solution or 1×10^{-4} M calcium chloride if started in a paper roll for best seedling root development. Leaves may become mottled if plants are grown under high humidity.

Cucumber, Melon, and Squash.—Vines of these plants will occupy a great deal of space unless staked up, and pruning is recommended to prevent excessive branching. When foliage is removed by pruning, the nutrient requirements are correspondingly reduced. When these plants are grown indoors, hand pollinating is required to obtain good fruit set, and thinning to control fruit size may be required. The squash variety 'Golden Nugget' is determinate and suitable for growing in a restricted space. It remains bushy with the fruits at the base of the plant. These species are all susceptible to mildew if grown under high humidity.

Endive.—This species develops a very extensive root system as compared with other species when grown hydroponically.

Flax and Red Clover.—Stem cuttings rooted in aerated water may also be used to propagate these species. After rooting, the cuttings are supplied with one-third strength solution. When grown in vermiculite, flax should be given small amounts of nutrient solution at any given time. Excess moisture will cause yellowing of lower leaves and nutrient stress will cause yellowing of upper leaves. Red clover can be grown well in screened frames (fig. 2) when one-fourth strength solution is used continuously.

Johnsongrass.—This species is easily grown from rhizome sections. Plant development is normal in vermiculite, but poor rhizome development is obtained when grown in liquid culture.

Millet, Sorghum, and Sudangrass.—Rust-colored blotches will occur on leaves of these species under high humidity.

Okra.—This species has low nutritional requirements, and older leaves will become senescent if the nutrient solution is allowed to become too concentrated.

Peanut.—This species grows well to maturity in vermiculite. Large containers should be used to permit normal fruit development. Young plants

should be watered sparingly to prevent root rot. Seed viability is much reduced after 1 year.

Plantain and Sunflower.—These species have very low nutritional requirements and are susceptible to mildew when grown under high humidity.

Potato.—When greenhouse-grown tubers are replanted in the greenhouse, the resulting vines may be spindly and tuber production poor.

Soybean.—When illumination is insufficient, internodes become greatly elongated, leaves become enlarged and the plants will fall over. At a high nutrient concentration the young leaves become cupped.

Sugarcane.—Solution culture of seedlings in troughs for more than 30 days is difficult because trough covers (fig. 2) will interfere with stem thickening. If seedlings are grown in fertile soil, little nutrient addition may be required in the first 4 weeks. Then, one-half strength solution can be supplied three times per week for the next 4 weeks, followed by a full-strength solution on the same schedule for the remainder of the growth period. In vermiculite use one-half strength solution three times per week. For further propagation, 10-cm. stem sections of mature plants, each bearing a node, may be layered in moist vermiculite, covered, and incubated for 5 to 7 days at 32° C. The sprouted sections will grow rapidly when transplanted to vermiculite and supplied with one-half strength solution. Sugarcane forms more tillers in vermiculite than in solution culture.

Sweetpotato.—This species is easily propagated by layering a vine and transplanting the vine sections that sprout at each internode. New sprouts 15 to 20 cm. long also may be removed from the root and planted. When sweetpotato is grown in liquid culture, the fleshy roots do not develop well.

Tobacco.—Reduce moisture stress for 48 hours after transplanting by lowering the temperature to about 18° C. and increasing the humidity.

Tomato.—Uneven watering of plants in vermiculite will result in ovary rot of developing fruit. Pollination can be promoted by tapping the plants or by using a fan. A determinate variety such as 'Sheyenne' is especially suitable where compact plants are desired.

Turnip.—This species has low nutritional requirements. Roots enlarge rapidly in solution culture.

Wild Buckwheat.—Newly harvested seed may remain dormant. Vines should be staked up adequately and spaced to prevent tangling.

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