Vegetable and field crop rooting depths and lateral root distances, revised.
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Table 1 lists the maximum rooting depth, lateral root distance from crown of plant and working root depth of vegetable crops at maturity, compiled from JE Weaver and WE Bruner, 1927. Root Development of Vegetable Crops (free download from http://soilandhealth.org).
Table 1

Vegetable crop	Variety	Age or date when root data collected	Root depth x lateral root distance, feet	Working root depth, feet
asparagus		6 year old	10.5 ft deep x 6 ft lateral	4.5'
beans, dry	Wardwell's Kidney Wax	5-Aug	3.8 x 2.5'	3'
beans, dry	Burpee's Bush Lima	25-Aug	5.5 x 4'	3.7'
beet, table	Edmand's Blood Turnip	1st yr 12 Aug	11 x 4'	7'
cabbage	Copenhagen Market	1st yr 4-Aug	7.8 x 3.5'	5.2'
cabbage	Early Flat Dutch	24-Jun	3.8 x 2.7'	
cantaloupe	Rocky Ford	24-Jul	3.7 x 15'	
cauliflower	Early Snowball	1st yr 19-Jul	4.5 x 2.5'	(3')
carrot	Chantenay	1st yr 12-Aug	10 x 2.3'	7'
chard, Swiss		1st yr 28-Jul	7 x 4.4'	(6')
corn, sweet	Stowell's Evergreen	late Aug	5.7 x 3.5'	4.2'
cucumber	White Spine	22-Aug	4 x 7'	3.7'
eggplant	Black Beauty	3-Oct	7 x 4'	
garlic		12-Jun	2.5 x1.5'	
horseradish		10 yr	15 x 3.5'	(12')
kohlrabi	Early White Vienna	1st yr 13-Aug	8.5 x 3.3'	7'
leeks	Large London	26-Jul	2.5 x 1.7'	(2')
lettuce	Early Prize Head	seed set 13 Jul	7.5 x 1.5'	5'
okra	Mammoth	22-Jul	4.5 x 6.6'	(4')
onions, dry	Southport White Globe	21-Aug	3.2 x 1'	2.7'
parsnip	Hollow Crown	1st yr 5-Oct	9 x 3'	
parsley,	Champion Moss Curled	1st yr 5-Aug	4 x 1.5'	
peas, fresh	Telephone	11-Jul	3.2 x 2'	(3')
pepper	Bull Nose	17-Jul	4 x 3'	(4')
potato, Irish	Early Ohio	8-Jul	5 x 2.5'	3'
potato, sweet	Yellow Jersey	3-Oct	5.7 x 3'	4.2'
pumpkin	Small Sugar	24-Aug	6 x 17.5'	(2.5')
radish	Early Scarlet Turnip White	flowering 13-Jul	7.2 x 4.1'	(4')
rhubarb,		4th yr summer	10 x 4.7'	(8')
rutabaga	American Purple Top	5-Sep	6.2 x 1.5'	5'
spinach	Curled Savoy	seed set 10-Jul	6 x 1.2'	(4')
squash, C. maxima	Golden Hubbard	21-Aug	6 x 19'	(2')
tomato	John Baer	13-Aug	5 x 5.5'	3.5'
turnip	Purple Top Globe	5-Oct	5.5 x 2.5'	5'
watermelon	Kleckley Sweet	26-Jul	4 x 21'	(2.5')

Table 2 lists maximum rooting depth, lateral root distance from crown of plant and working root depth of field crops at maturity, compiled from JE Weaver, 1926. Root Development of Field Crops (free download from http://www.soilandhealth.org).

Table 2

Field crop	Variety	Age or date when root data collected	Root depth x lateral root distance, feet	Working root depth, feet
alfalfa		2nd yr Jun	12 x 1.5'	
barley	Manchuria	grain ripe	6.5 x 1'	(3.5')
beet, sugar	Kleinwanzlebener	1st yr Sept	6 x 2'	
clover, red		2nd yr	10 x 1.5'	
clover, white sweet		2nd yr	8 x 1.5'	
corn, field	Iowa Silver Mine	2-Sep	8 x 4'	3.3
oats, spring	White Kherson	at harvest	5 x 0.8'	2.5'
potato, Irish	Early Ohio	8-Jul	3.8 x 2.5'	3'
rye, winter	Rosen	at harvest	5 x 0.9'	4'
rye, winter	2nd site, silty clay loam soil		5.2 x 1'	4.7'
rye, winter	3rd site, sandy loam soil		7.5 x 1.2'	5'
sorghum	Black Amber	maturing seeds	6 x 3'	4'
sunflower	Russian	21-Jul	9 x 5'	4'
wheat, spring	Marquis	harvest 15-Jul	5 x 1'	3.5'
wheat, spring	at Burlington, Colorado, dry farmed		2.7 x 1	
wheat, winter	Kanred	harvest 15-Jul	6.2 x 0.7'	4.4'
wheat, winter	2nd site, clay intermix at 2.3' depth		4.7 x 0.7'	3.2'
wheat, winter	3rd site, deep loess silt loam subsoil		7.3 x 0.7	4.9'

1. Root depths and lateral distances of vegetables were from crops grown to maturity at Lincoln, Nebraska, and Norman, Oklahoma, USA. The Nebraska site had friable silt loam soil; easily worked to depth greater than 12 feet; earthworm burrowed to a depth of 8 feet; average annual precipitation of 29 inches; and 21.6 inches of rainfall occur during April to September. The Oklahoma site had fine sandy loam soil; average annual precipitation of 39 inches; and 24 inches of rainfall occurs during April to September. At the beginning of the growing season, soil moisture was available for plant uptake throughout the crop rooting depths at both locations. Crops were grown without irrigation but receive rainfall.
2. Field crop data were collected from crops grown in Lincoln, Nebraska; except for sugar beet and a spring wheat test site, they were from Colorado.
3. The working depth is a depth to which many roots penetrate and considerable absorption must take place. Numbers without parenthesis were explicitly stated as 'working depth' by the authors. Numbers in parenthesis were inferred from the authors description (soil volume thoroughly occupied by roots), but they did not explicitly state the 'working depth'. No working depth was inferred for crops with root density that gradually shifts from thoroughly occupying a soil volume to sparse root density.
4. Plant root depth and lateral distance are affected by soil texture, structure, compaction, aggregates, fertility, water content and organic matter content. Table 2 provides examples of this: spring wheat grown at Burlington, Colorado with dry subsoil at 2.7 feet below the surface had a corresponding rooting depth of 2.7 feet. Winter wheat grown in

an area with compacted subsoil at 2.3' below the surface reduced the maximum rooting depth to 4.7' at the 2nd wheat site; whereas deep loess subsoil yielded a 7.3' rooting depth at the 3rd wheat site, both within 2 miles from the main Nebraska test site. Winter rye grown at 3 different sites in Nebraska with different soil profiles had different rooting depths. Weaver and Bruner data are approximations when applying other soils.

5. Plant rooting depths for irrigated crops are available on the internet; however, crops under light frequent irrigation develop shallower roots compared to crops with infrequent or no irrigation.

Implications for Oregon dry farm test plots:
1. Pumpkin, winter squash and watermelon can have lateral roots extending 17.5 to 21 feet from crown of plant to extract water. Trials of dry farmed squash and watermelon grown within lateral root distance to adjacent irrigated crops will yield misleading results about dry farmed squash and watermelon.
2. Yield and crop water use data from two different dry farmed crops, grown within lateral root distances of each other are difficult to interpret with regards to the crop's performance under dry farmed conditions.
3. Grass walkways between crop rows will extract water stored in the soil profile below the grass. Grass may send lateral roots into the crop row; and crops may send lateral roots below the grass walkway. When grass evapotranspiration (ET) exceeds rainfall, the grass walkway should be removed. When grass ET is less than rainfall, the grass intercept rain water that otherwise contribute to surface runoff or below surface percolation. For normal monthly rainfall and normal monthly grass ET, the walkway vegetation should be removed sometime in April or early May, for Aurora, Corvallis, and Forest Grove; sometime in March or early April for Medford. This is determined using monthly grass ET and rainfall data. Monthly grass ET data were obtained from AgriMet http://www.usbr.gov/pn/AgriMet.html   > crop water use information > Monthly Average Reference Evapotranspiration; and convert ET(alfalfa) to ET(grass) by dividing ET(alfalfa) by 1.2. Monthly rainfall data are from www.usclimatedata.com

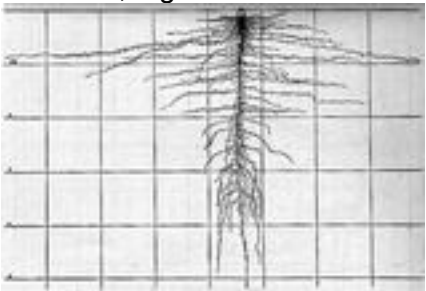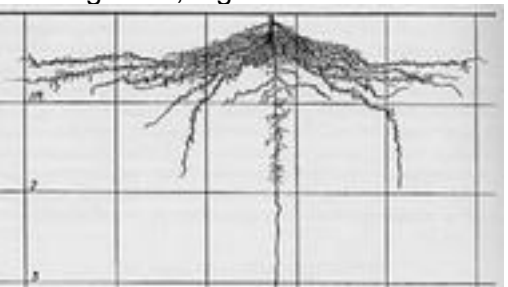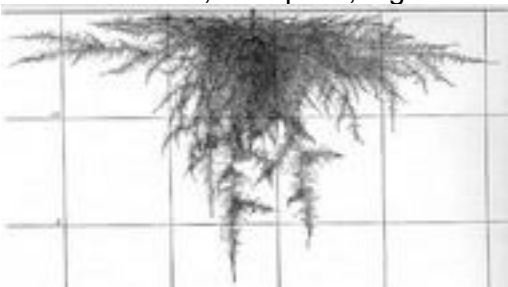|	March	April	May
Aurora, Oregon	1.7"ET 4.2" rain	2.8"ET 3.1" rain	4.2" ET 2.3" rain
Corvallis	1.9" 4.4"	2.9" 2.9"	4.4" 2.3"
Forest Grove	1.7" 4.7"	2.7" 3.1"	4.3" 2.2"
Medford	2.0" 2.2"	3.1" 1.6"	4.9" 1.4"
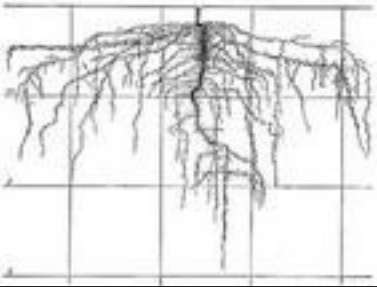
4. Nearby trees can send roots 100 feet or more from the trunk and extract soil water below the surface. Dry farm test plots within range of tree roots will be adversely affected.
5. Question: should the volume of soil explored by roots be calculated using lateral root distance and working root depth, or lateral root distance and maximum root depth; should planting density for dry farmed crops be calculated based on the working root depth or the maximum root depth? A conjecture here, the working root depth is where yield counts, thus calculations should be based on the working root depth. The maximum root depth is a plant survival trait allowing plants to survive but deep roots below the working root depth does not contribute significantly the marketable yield for the farmer. There are several basic rooting systems. Pancake rooting system has shallow roots with large lateral distances. For example squash have 19 feet lateral roots with 2 feet working depth and a 6 foot tap root. Most of the water and nutrients are extracted from the pancake layer. Calculations of soil volume explored by roots using the lateral root distance and working root depth would slightly underestimate the volume; whereas using maximum root dept would significantly overestimate the soil volume explored by roots. Turnip, pea and alfalfa have cylindrical root systems; the working root depth is nearly the same as the maximum root depth and calculation of the volume of

soil explored by roots using working root dept is nearly the same as using maximum root depth. Carrot and parsnip have parabolic or inverted cone root system; the difference in calculating soil volume explored by roots using working root depth or maximum root depth is between that for a pancake and a cylindrical root system.

Additional notes, January 2021

Root drawings
Selected drawings of young vegetable roots from Root Development of Vegetable Crops by Weaver and Bruner (1927) are provided below. Crop drawings are in alphabetical order with age of root (days) grown from seed unless specified as transplant; and figure number used in the book. For okra and potato, only half of the root system was drawn due to root density. Field corn and potato drawings were from Root Development of Field Crops (1926) by JE Weaver. For complete set of root drawing, see original.

Bean, 57 days, Fig 55	This area left blank
Beet 42d, Fig 19	Beet 68d, Fig 20
Cabbage 55d, Fig 28	Cauliflower 57d, transplant, Fig 36

Chard 25d, Fig 23
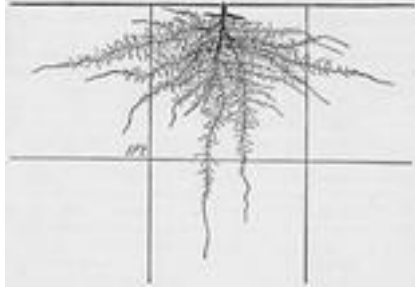
Chard 49d, Fig 24
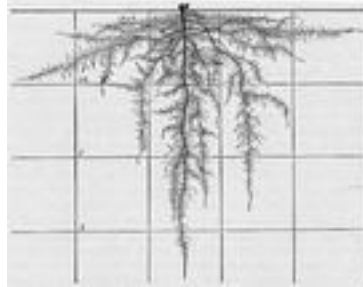
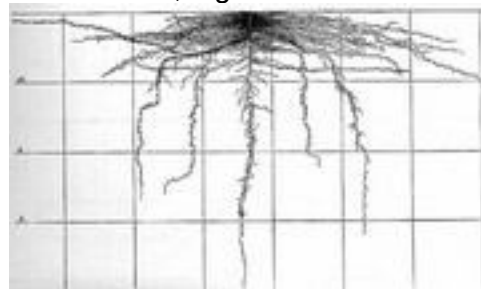Cucumber 27d, Fig 81
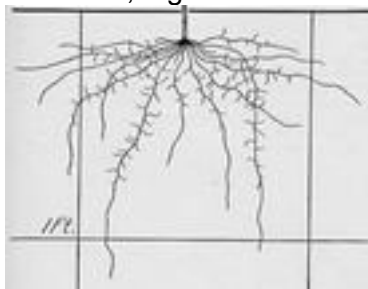
Cucumber 41d, Fig 82
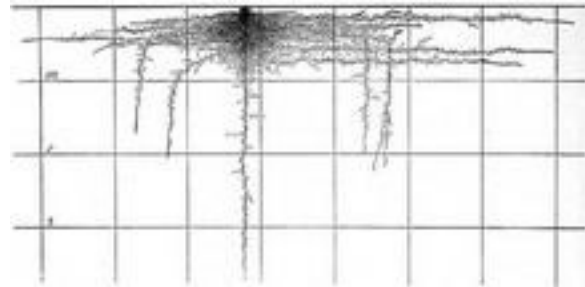
Eggplant 52d,, Fig 77
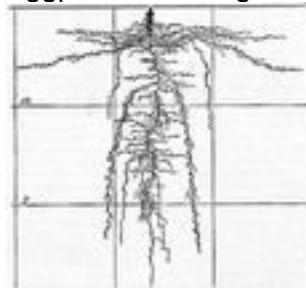
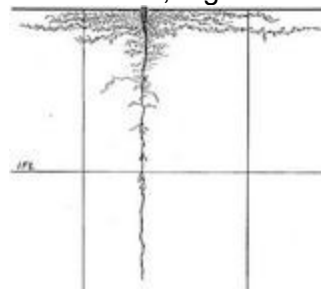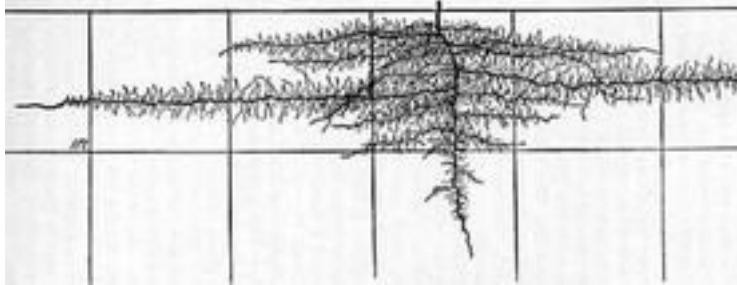Field corn 57d
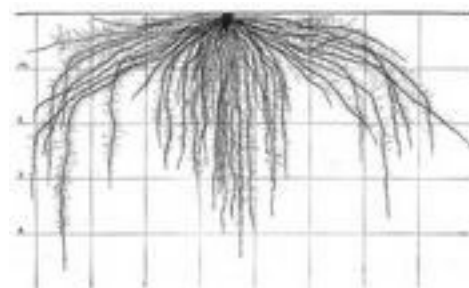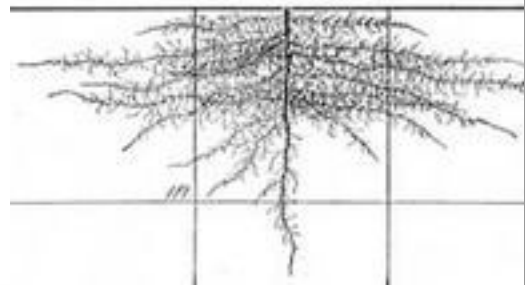
Kohlrabi 44d, Fig 38
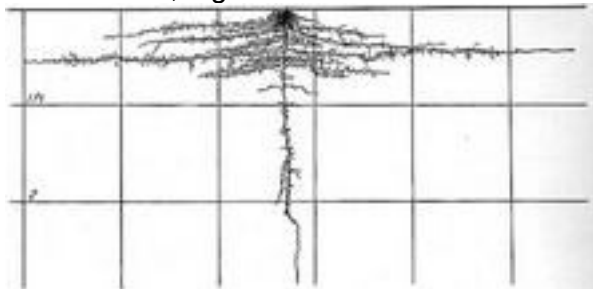
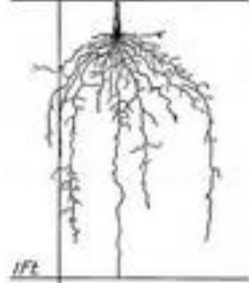Kohlrabi 64d, Fig 39

Leek 64d, Fig 11

Lettuce 38d, Fig 91

Muskmelon 35d, Fig 84	Okra 23d, half root system, Fig 59

Onion 55d, Fig 7	Parsley 57d, Fig 64

Parsnip 55d, Fig 65	Peas 43d, Fig 51
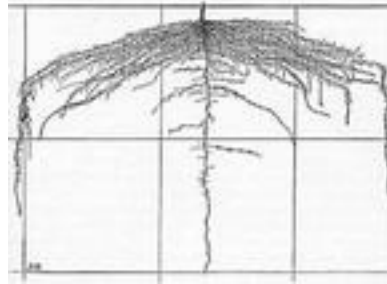
Pepper 24 d transplant, Fig 78	Pepper 39d, transplant, Fig 79
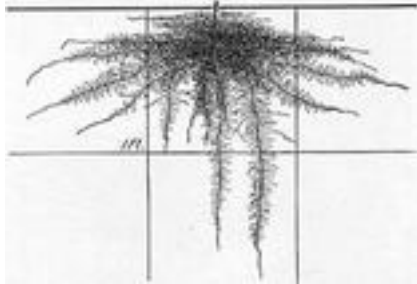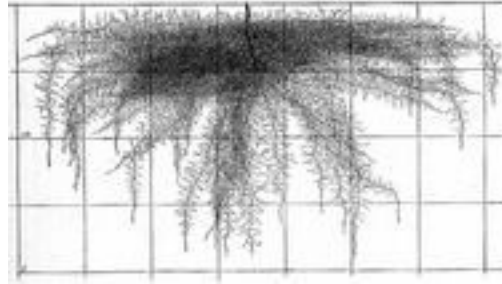
Potato 56d, half root system	Pumpkin 20d, Fig 90
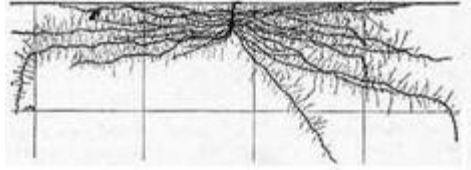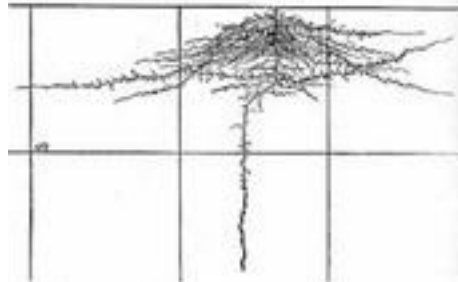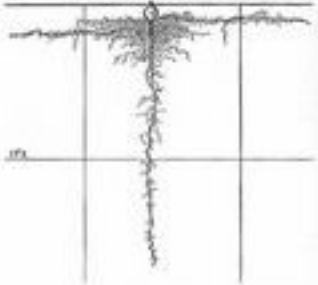
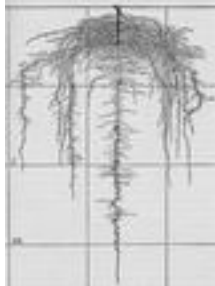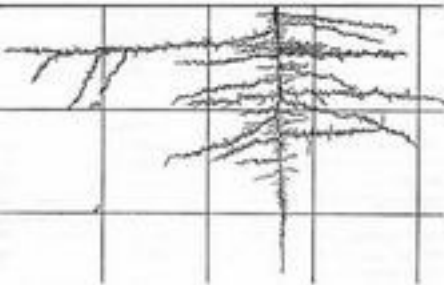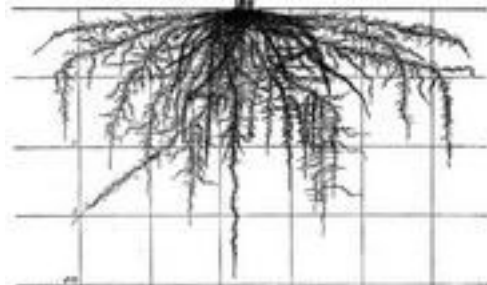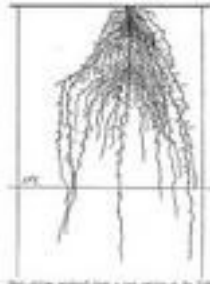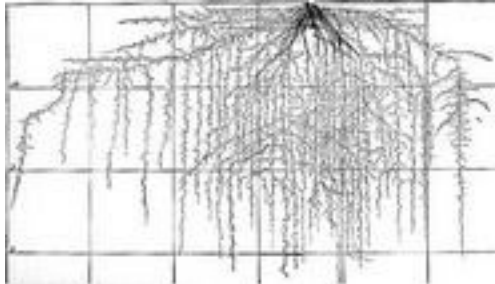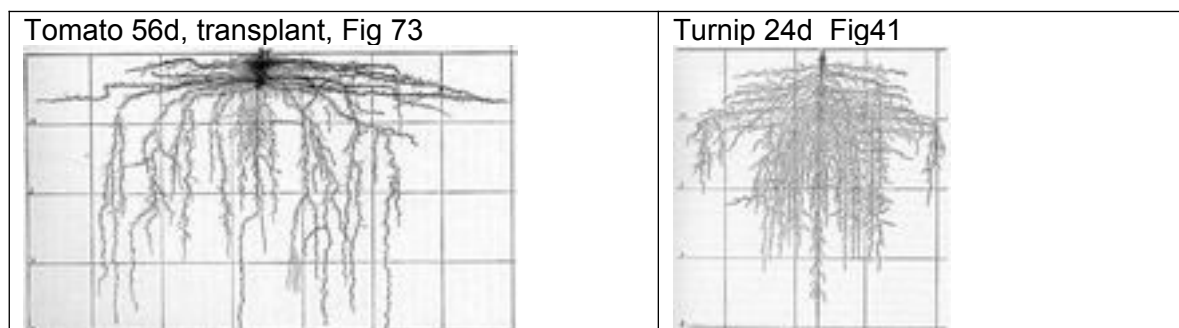| Radish 38d, Fig46	Radish 62d Fig47
Rutabaga 24d, Fig 43	Rutabaga 41d, Fig 44
Spinach 43d, Fig 26	Spinach 68d, Fig 27
Squash 41d, Fig 87	Sweet corn 55d, Fig4
Sweet potato 23d, transplant, Fig 68	Sweet potato 55d, transplant, Fig 69
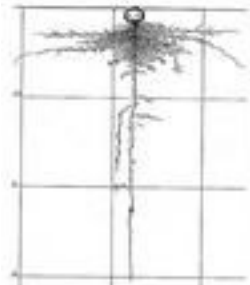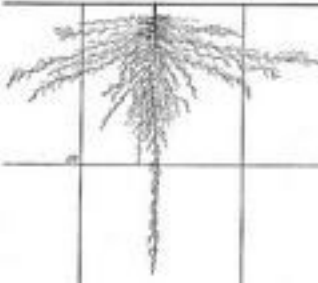
| Tomato 56d, transplant, Fig 73 | Turnip 24d Fig41 |

Estimating crop root surface area at 56 days after planting

Crop root surface area was estimated as follows: convert the grayscale drawings of roots into binary images (monochrome black or white). Next, count the number of black pixels in the binary images, representing roots; and count the total number of pixels in a square foot area. The background grid lines in the drawings are spaced 1 foot apart. Then divide the number of black pixels (roots) by the number of pixels in a square foot to arrive at the root surface area of the plant, in square foot units. Organizing the crops by age and root surface area reveals crop root growth vigor; crop with vigorous early root growth are ideal for dry farming.

Crops were grouped by age, in weeks +/- 3 days. None of the age groups contains all crops. The age group with the largest number of crops was the 8-week group, followed by 6-week group. To fill in additional data, crop root surface area of older crops was extrapolated back to an earlier growth date. Root surface area of crops older than 56 days (8 weeks) were extrapolated backward to 56 days by assuming exponential root growth rate. However, extrapolating root area of young crops forward to 56 days was subject to small errors that magnifies exponentially.

The increasing order of root surface area of crops at 8 weeks of growth (56 days +/- 3) is as follows; older crops extrapolated to 8 weeks of growth in parenthesis:

Onion < (leek) < parsley < parsnip < (radish) < (spinach) < (lettuce) < (kohlrabi) < cabbage < bean < potato < cauliflower < sweet potato < tomato < field corn < sweet corn.

The list of all crops in increasing order of root surface area using calculated root area and extrapolated root area of crops younger and older than 56 days, adjusting for exponential magnification errors and grouped into similar root surface area, along with best guess is as follows:

[carrot = leek = onion = parsley = parsnip = radish = (0.06-0.31 sq ft root area)] <
[beet = eggplant = lettuce = spinach = (0.82-0.92 sq ft)]   <
[bean = cabbage = kohlrabi = (1.4-1.5 sq ft)]   <
[cauliflower = pea = potato = (2.01-2.4 sq ft)]   <
[chard = cucumber = field corn = muskmelon = okra = pepper = potato = rutabaga = squash = sweet corn = sweet potato = tomato = turnip = (3-6? sq ft)]

Method for computing root area from grayscale drawings is as follows:
1. Make 2 copies of the root drawings
   a. Use one copy to measure the number of pixels per square foot; the grid lines are 1 ft apart on the x and y axis.

b. On the second copy, erase the grid lines; otherwise the grid lines would be counted as root

2. Using the root drawings without grid lines, convert the grayscale image to binary. Softwares used were: 'ImageJ' (available as free download from National Institute of Health), 'Image MagicK' (available as free download) and 'Adobe Photoshop'. 'ImageJ' and 'Image MagicK' have default cut-off threshold for converting grayscale pixel to either black or white. Adobe Photoshop and ImageJ allow users to select cut-off threshold. Threshold value of 178 converts 11/16th of the shades of grey as black; threshold value of 195 converts 3/4th of the shades of grey as black.

   a. Convert with ImageJ > open file > process > binary > make binary. Count the number of black pixels with ImageJ > analyze > histogram > list > value 255 = black, because of an inverted look-up-table; record the 'count'.
   b. Convert with Photoshop > open file > image > adjustment > threshold > adjust to 178 or 195 > ok. Count the number of black pixels with Photoshop > image > histogram > select level = 0 and record the 'count'.
   c. Converting with Image MagicK requires 'terminal' input in Linux using the command 'convert –monochrome in.jpg out.jpg'

3. Check the binary images and erase stray marking and dithering speckles if present, then reconvert the image to binary and recount the number of black pixels.

4. Calculate root surface area: divide [number of black pixels (root)] by [number of pixels/sq ft in the image] = area of roots, sq ft.

5. Extrapolation of root area assuming exponential growth:
   a. Multiply the computed root area by 100 to avoid log of values less than1. This facilitates plotting of data on a graph for visual inspection and using (0,0) at planting with zero root growth; log values greater than zero and less than 1 is negative; log of zero is minus infinity.
   b. Find the slope of the growth rate using 2 different growth dates: [(ln (100 * root area at date2)– ln (100 * root area at date1)] / [(root age at date2 – root age at date1)] = ln 100 growth rate per day
   c. Extrapolate the root area for 56 days (8 weeks): ln(100*root area at date1) + slope *(56 days – days at date1) = ln 100 root area at 8 weeks
   d. Convert ln root area back to sq ft: [Exp (ln root area)] /100 to cancel the 100 multiplication factor.

6. All 3 softwares for converting grayscale image to binary image yielded the same sequence of root surface area in crops, although the number of black pixels may differs. The computed root surface area does not account for technical issues such as accuracy of root drawings, the transfer of drawings to book and book to digital format, removal of grid lines from drawings without affecting root surface area measurements and effectiveness of software algorithm in converting grayscale to binary. Unaccounted factors include planting date, crop variety, weather, soil characteristics etc

Results: crop root surface area using ImageJ data of younger and older crops, extrapolated to 56 days of growth, grouped into similar root surface area, in increasing order:

Crop	Age, days*	Root surface area at 56 days, sq ft**
onion	55	0.06
leek	64	0.08
parsley	57	0.09
carrot	47	0.14
parsnip	81	0.18
radish	62	0.31

beet	68	0.82
spinach	68	0.86
lettuce	62	0.89
eggplant	52	0.92
kohlrabi	64	1.41
bean	57	1.50
cabbage	75	1.54
cauliflower transplant	57	2.01
potato half root x 2	56	2.01
pea	43	2.36
sweet potato transplant	55	3.14
tomato transplant	56	3.39
chard	49	3.79
squash	41	4.38
field corn	57	4.69
sweet corn	55	5.82
rutabaga	41	6.88
turnip	41	10.36
cucumber	41	11.78
muskmelon	35	25.41
pepper transplant	39	89.43
pumpkin	20	306.98
okra half root x 2	23	631.73

* Age is the plant root age used to extrapolate to 56 days of growth, assuming exponential growth rate.

** Area is square foot of root surface per plant, when extrapolated to 56 days of growth

Highlighted in yellow are crops much younger than 56 days with magnification error in extrapolating exponential root growth to 56 days.

Crops were grown from seed unless specified as transplant. For potato and okra, the computed root surface area is twice the value obtained from the drawings because only half of the roots were drawn.