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OAK RIDGE NATIONAL LABORATORY

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A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides through Agriculture

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Section 3

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3. INTERCEPTION FRACTION FOR VEGETATION

The interception fraction for a given vegetation type, r^i, is a factor which accounts for the fact that not all of the airborne material depositing within a unit area will initially deposit on edible vegetation surfaces. The fraction of the total deposit which is initially intercepted by vegetation is the interception fraction, r^i, such that $0 \leq r^i \leq 1$. In the TERRA code, as in other food chain transport models,[6] the processes of initial deposition and weathering removal with time are treated separately. In the NRC Regulatory Guide 1.109 model, separate interception fractions are suggested for iodines and other particulate types.6 The analysis of agricultural food and feed crops in the United States by Shor, Baes, and Sharp[7] suggests that the diversity of growth forms necessitates vegetation-specific estimates of interception fraction as well. The following sections outline a theoretical approach to vegetation-specific interception fractions. The results of such approaches have been used as default estimates in lieu of user-input values in the TERRA computer code. Variation of interception fraction with element, chemical form, and deposition process (e.g., wet, dry) will require further research.

In Section 3 pasture. hay, and silage productivities are considered to be on an air-dry weight basis as reported in reference 7. Vegetable and produce productivities are in fresh weight as reported in reference 7.

3.1 Pasture Grasses and Hay

The interception fraction for pasture grasses and hay are modeled in a different manner than for other vegetation types because experimental determinations of interception fractions for grasses have been performed.[192-198] In these studies a correlation between initial interception fraction and productivity (standing crop biomass) has been found. This relationship and an empirical fit of the available data (summarized in Table 3.5 of reference 199) is shown in Figure 3.1. The empirical relationship is given by

$$r^{pg} = 1 - \exp(-2.88 Y_{pg}) \tag{10}$$

where

r^{pg} = the interception fraction for pasture grass and
Y_{pg} = the productivity of pasture grass (kg/m^2, dry).

This relationship has been assumed to apply to hay as well as pasture grasses in the computer code TERRA.

3.2 Leafy Vegetables

There are no readily available literature references for the interception fraction for leafy vegetables. Therefore, the interception fraction for leafy vegetables is based on a theoretical model (Fig. 3.2). With this model a range of possible interception fractions may be generated if the following assumptions are made:

1. On a two-dimensional basis the fractional area represented by leafy vegetables is equal to the interception fraction;
2. leafy vegetables may be represented by circles on a two-dimensional basis (Fig. 3.2);
3. leafy vegetables are planted in rows;

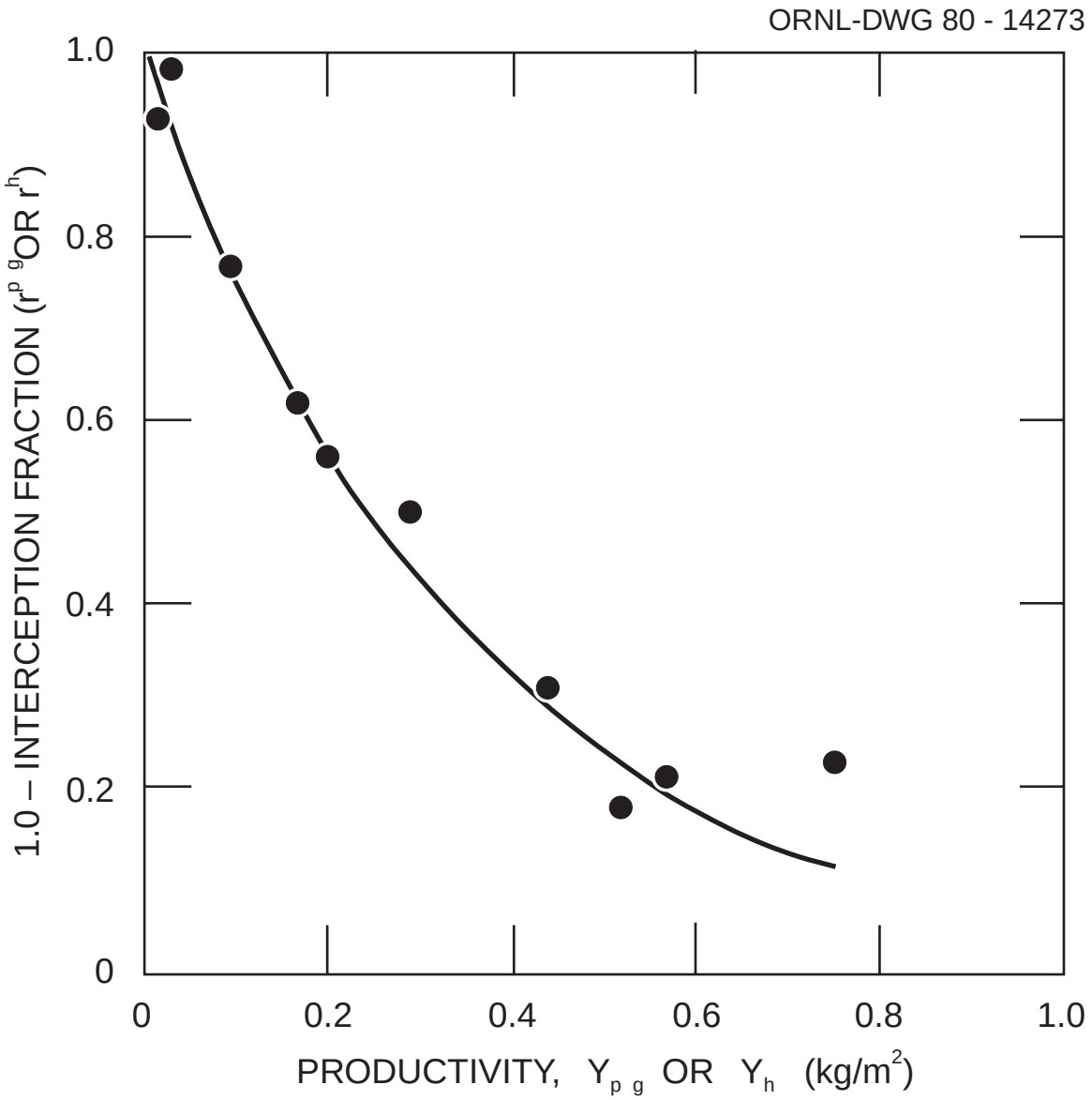

Figure 3.1. Relationship between interception fraction and productivity (in dry weight) for forage grasses (pasture and hay).

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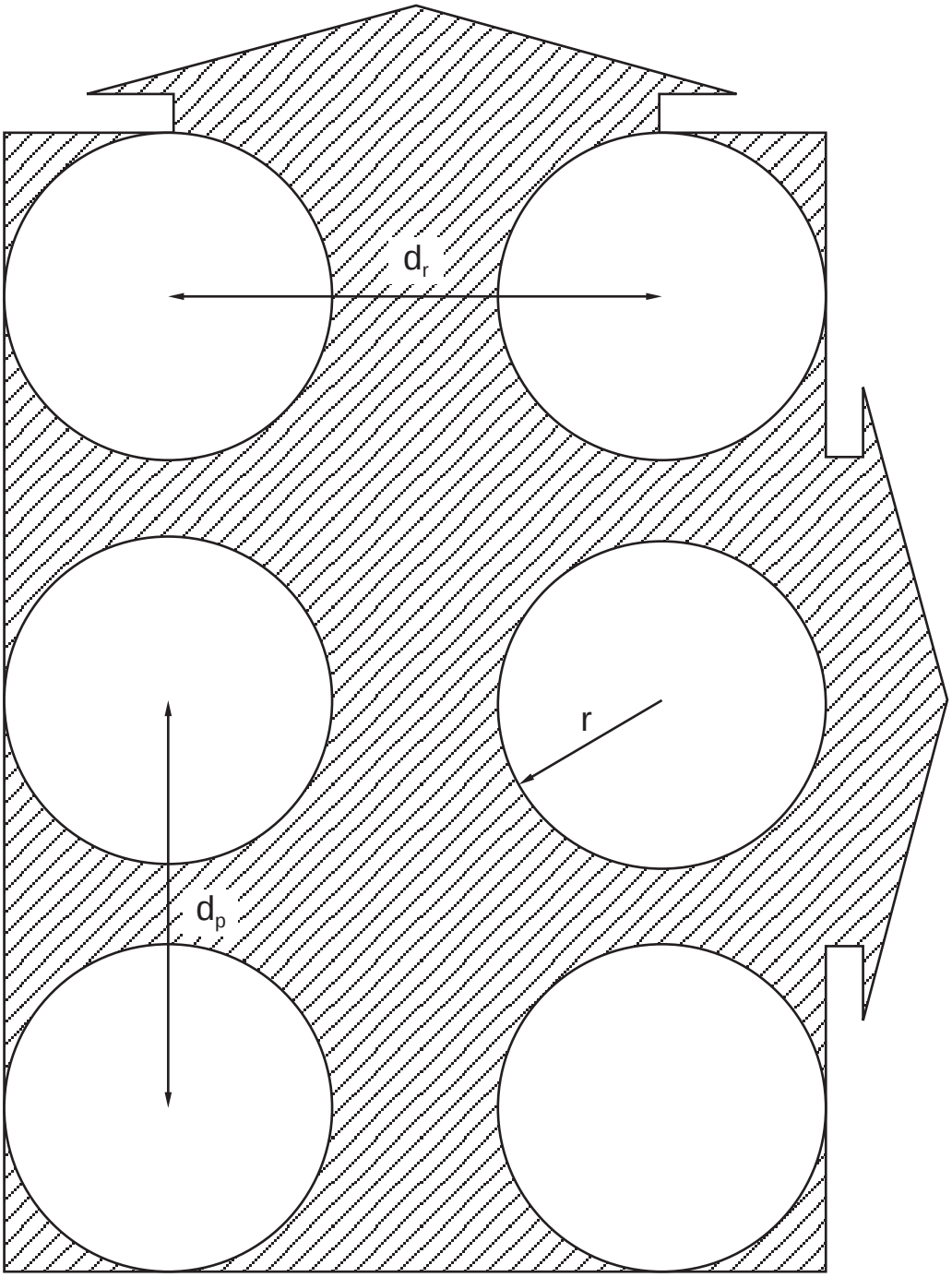

CONSTRAINTS: $2r \leq d_p \leq d_r$

Figure 3.2. Model of field geometry of leafy vegetable spacings.

4. the ranges of between-plant and between-row spacings in the United States are approximately equal to the minima and maxima recommended by Knott;[200]
5. a farmer will not plant individual leafy vegetables so close together that leaves from adjacent plants overlap (thereby decreasing yield);
6. rows will generally be spaced farther apart than individual plants in a row; and
7. harvest of leafy vegetables occurs at the time of maximum yield, and maximum yield corresponds to maximum plant diameter.

With the above assumptions, the model given by Fig. 3.2 predicts that the fraction of planted area occupied by leafy vegetables, equivalent to the interception fraction at harvestable maturity, is given by

$$r^{mlv} = \frac{n_r\, r_n\, \pi r_f^2}{[(n_r - 1)d_p + 2r_f][(r_n - 1)d_r + 2r_f]}, \tag{11}$$

where

r^{mlv} = the interception fraction for mature leafy vegetables,
n_r = the number of plants per row,
r_n = the number of rows of plants,
r_f = the radius of an individual fruit or plant,
d_p = the distance between plants in a row, and
d_r = the distance between rows of plants.

The constraints on the model are

$$2r_f \le d_p \le d_r. \tag{12}$$

As the land area planted becomes infinitely large, Eq. (11) becomes

$$r^{mlv} = \frac{\pi r_f^2}{d_p d_r}. \tag{13}$$

If a farmer maximizes the number of plants per row such that $d_p = 2r_f$, then Eq. (13) becomes

$$r^{mlv} = \frac{\pi r_f}{2d_r}. \tag{14}$$

When $2r_f = d_p = d_r$ (maximum utilization of planted land), then the interception fraction for mature leafy vegetables is 0.785.

In order to predict an average interception fraction for the mature leafy vegetable, recommended field spacings[200] for leafy vegetables were assumed to represent typical spacings actually encountered in American agriculture. A distribution of field spacings was determined by obtaining a range of recommended spacings for each leafy vegetable and weighting each vegetable according to its importance (by area planted) in the United States (Table 3.1). By determining distributions of typical d_r spacings and values of r_f, a Monte Carlo technique was used to produce a distribution of solutions to Eq. (14). The mean value of this distribution is $r^{mlv} = 0.30$. In this simulation the average d_r was 73.5 cm (28.7 inches).

Table 3.1. Weighting factors for leafy vegetable interception fraction model simulation

Leafy vegetable	Quantity planted (km^2)	Percent	Weight factor
Lettuce	948	42	
cos			14
head			14
leaf			14
Cabbage	367	16	
early			6
late			5
Chinese			5
Greens	246	11	
collards			3
kale			3
spinach			3
New Zealand spinach			2
Broccoli	176	8	
sprouting			4
raab			4
Mint	160	7	7
Celery	140	6	6
Cauliflower	113	5	5
Green onions	59.3	3	3
Escarole	33.6	2	
chicory			1
endive			1
Brussels sprouts	24.8	1	1
Total	2267.7	100	100

From the theoretical interception fraction for mature leafy vegetables of 0.30 it is possible to generate an average interception fraction over the time in the field by taking into account the logistic growth characteristics of plants (Fig. 3.3). It is commonly known that plants (and many living organisms) have growth patterns which follow a logistic growth pattern.[201-205] Logistic growth curves have been defined by various equations which yield the appropriate shape. For our analysis the following equation was used:

$$f^m = \frac{1 - \cos[180(\frac{t_i}{t_m})]}{2}, \tag{15}$$

where

f^m = the fraction of maximum growth,
t_i = the time of interest, and
t_m = the time at which maximum growth normally occurs

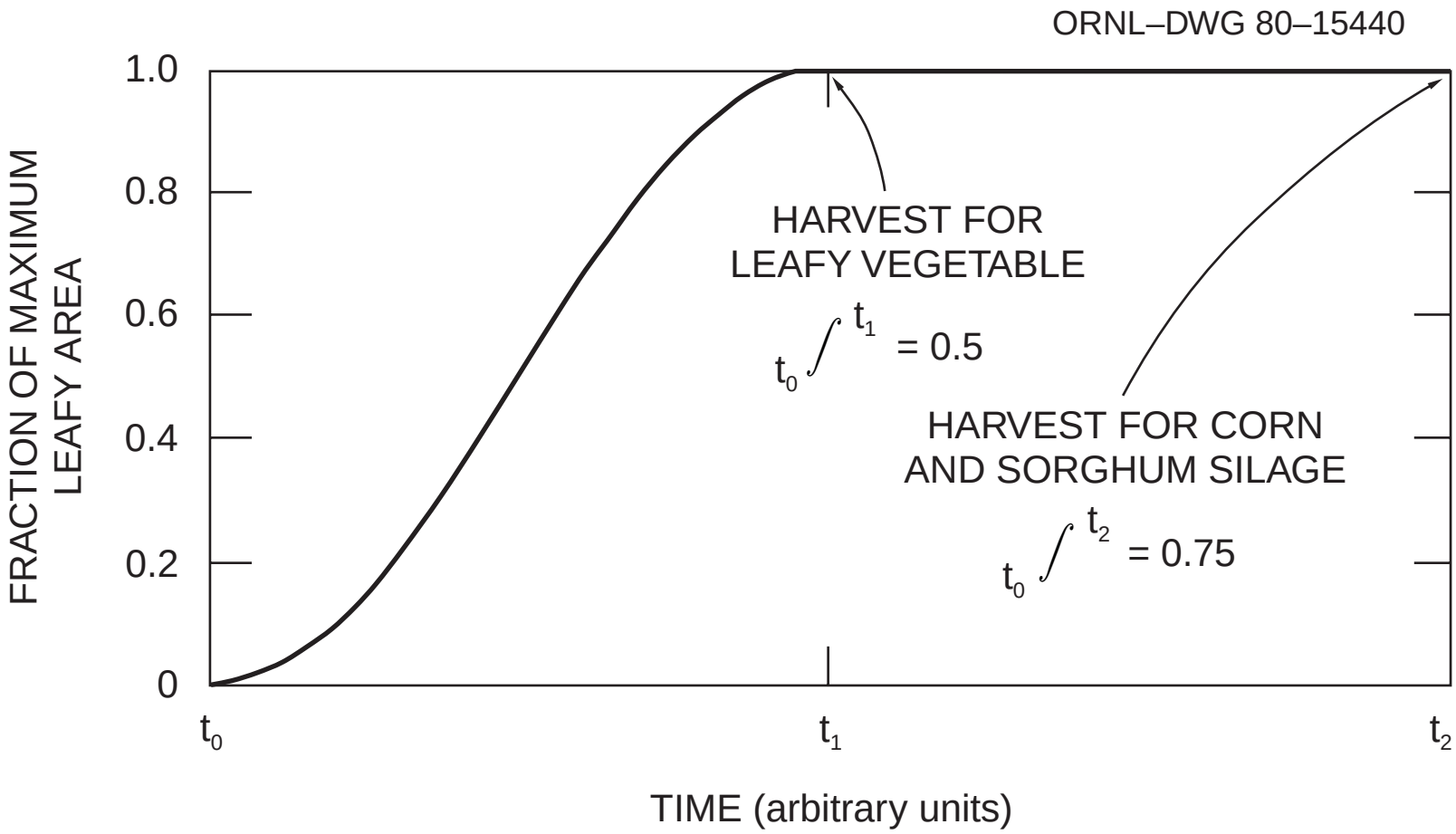

Figure 3.3. Hypothetical growth curve for plants. Leafy vegetables are harvested at the time of maximum growth, and silage is harvested at grain maturity.

Equation (15) was chosen because at time = $t_m/2$, $f^m = 0.5$ and integration of Eq. (15) from t_0 to t_m yields 0.5. Thus, an average interception fraction for leafy vegetables over the time in the field is equal to 0.5×0.30 or 0.15. It must be emphasized that the value of 0.15 represents a theoretical average over the United States for leafy vegetables. A corresponding theoretical maximum would be 0.5×0.785 or 0.39.

3.3 Silage

The analysis of silage interception fraction is based on an approach similar to that for leafy vegetables. A modification of the two-dimensional model was made to allow for overlap of leaves from adjacent plants (as seen in aerial views of corn and sorghum fields). However, no overlap was allowed between leaves from adjacent rows (Fig. 3.4). It was assumed in our analyses that the silage is not harvested until the grain has matured. This period of maturity corresponds to the period t_1 to t_2 in Fig. 3.3. According to descriptions of growth stages in corn by Hanaway[206] and Norman,[207] grain maturity occurs at a time approximately equal to twice the time to maximum plant growth (and thus maximum surface area). Accordingly, the integral of plant surface area from t_0 to t_2 in Fig. 3.3 is 0.75.

From Fig. 3.4, the fraction of total area occupied by the silage at maturity is given by

$$r^{ms} = \frac{r_f^2\left[\frac{4\pi}{3} + (n_r - 1)\frac{\sqrt{3}}{2} + (n_r - 2)\frac{\pi}{3}\right]r_n}{[d_r(r_n - 1) + 2r_f][d_p(n_r + 1)]}. \tag{16}$$

The model constraints are

$$r_f = d_p \le \frac{d_r}{2}. \tag{17}$$

As the planted area becomes infinitely large, Eq. (16) approaches

$$r^{ms} = \frac{r_f^2\left[\frac{\pi}{3} + \frac{\sqrt{3}}{2}\right]}{d_r \cdot d_p}. \tag{18}$$

Since $d_p = r_f$, Eq. (18) becomes

$$r^{ms} = \frac{d_p\left[\frac{\pi}{3} + \frac{\sqrt{3}}{2}\right]}{d_r}. \tag{19}$$

At maximum silage density ($d_r = 2d_p$) Eq. (19) becomes a value of 0.96. Correspondingly, the maximum average interception fraction is equal to 0.72.

The average interception fraction was derived from average values of d_r and d_p for corn and sorghum plantings. An average d_p of 30.5 cm (12 inches) and d_r of 99 cm (39 inches) was taken from Knott[200] and Rutledge.[208] Using these values, an interception fraction at maturity of 0.59 was determined from Eq. (19). This value yields an average interception fraction of 0.44.

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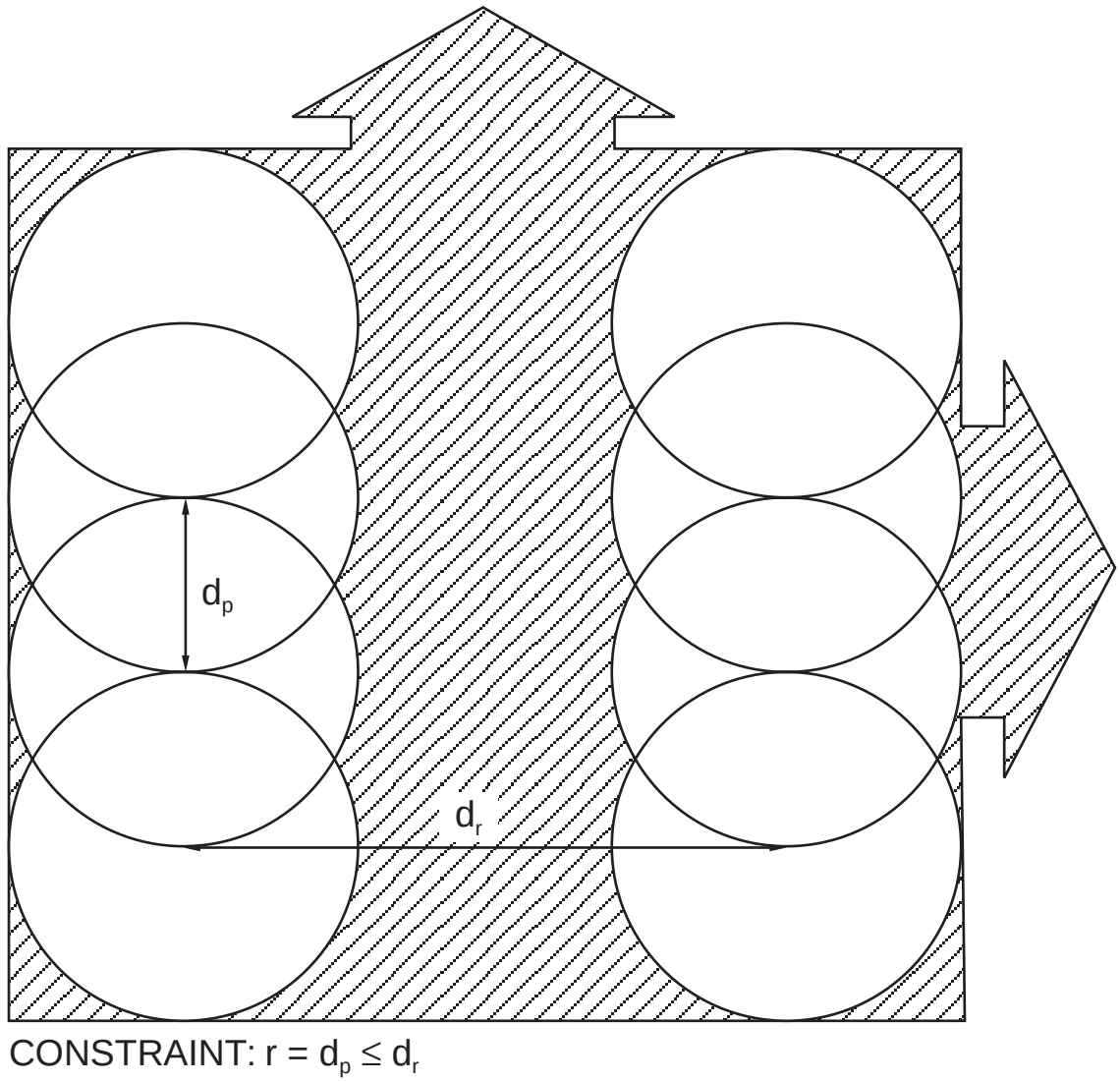

Figure 3.4. Model of field geometry of silage plant spacings.

3.4 Exposed Produce

The exposed produce category includes 31 commercially important fruits and vegetables in the United States.[7] These produce may be broadly classified as noncitrus fruits, berries, and important field crops. Because of the diversity of growth forms in the exposed produce category, our analysis is based on five of the most important noncitrus fruits and field crops in the category—apples, snap beans, tomatoes, peaches, and cherries. For this analysis, importance is defined in terms of area planted (see Table 3.2).

For noncitrus fruits and tomatoes, as with leafy vegetables and silage, it is assumed that the fruits can be represented by circles on a two-dimensional basis. The interception fraction is calculated by determining the total fruit cross-sectional area per square meter which is given by

$$r^{mf} = \frac{n\pi r_f^2}{lw}, \tag{20}$$

where

r^{mf} = the interception fraction of the mature fruit,
n = the number of fruit per square meter
r_f = the radius of the fruit (mm),
l = the length of the unit area (1000 mm), and
w = the width of the unit area (1000 mm).

It is assumed that an average interception fraction over the lifetime of the fruit is provided for by the model of logistic growth and maturity used for silage. That is, half of the fruit's residence time in the tree or on the plant is assumed to be for growth and development, and one half of the time is assumed to be for maturing or ripening before harvest. Thus, Eq. (20) becomes

$$r^{ef} = \frac{0.75 n\pi r_f^2}{lw}, \tag{21}$$

where

r^{ef} = average interception fraction for exposed fruit.

For snap beans the same approach as for round fruits is used, except that the effective surface area of a snap bean is modeled in two dimensions as a rectangle—a two dimensional view of a cylinder on its side. For mature snap beans

$$r^{msb} = \frac{n2r_f l_f}{lw}, \tag{22}$$

where

l_f = the length of the snap bean.

As with tree fruits and tomatoes, the average interception fraction over the time in the field is 0.75 times the value of the mature interception fraction.

A search of the literature was performed to determine values of n, r_f, r_l, and l_f or collateral information from which to deduce them. Empirical measurements of r_f and r_l were combined with literature values to determine default values. Fruit weights were compared with estimated weights of spheres of water of the same radius to check default estimates. Information from the 1974

Table 3.2. Relative importance of various exposed produce in the U.S.

Vegetable	Quantity planted (km^2)	Percent of category	Percent of sub-category
Non-citrus tree fruits			
Apple	1960	27.2	57.3
Apricot	6.00	0.1	0.2
Cherry	429	6.0	12.5
Date	0.101	≤0.1	≤0.1
Fig	0.0647	≤0.1	≤0.1
Mango	4.86	≤0.1	0.1
Nectarine	3.63	≤0.1	0.1
Peach	644	9.0	18.8
Pear	229	3.2	6.7
Hot Pepper	48.2	0.7	1.4
Plum	36.6	0.5	1.1
Prune	61.4	0.9	1.8
Total	3423	47.6	
Berries & vine fruits			
Blackberry	94.5	1.3	10.6
Blueberry	154	2.1	17.3
Boysenberry	4.75	≤0.1	0.5
Cranberry	91.2	1.3	10.2
Currant	1.12	≤0.1	0.1
Gooseberry	0.348	≤0.1	≤0.1
Grape	411	5.7	46.1
Pimento	1.64	≤0.1	0.2
Rasberry	29.9	0.4	3.4
Strawberry	104	1.5	11.7
Total	892	12.4	
Field crops			
Asparagus	269	3.7	9.3
Cucumber	380	5.3	13.2
Eggplant	16.0	0.2	0.6
Okra	16.7	0.2	0.6
Rhubarb	6.80	0.1	0.2
Sweet pepper	155	2.2	5.4
Snap bean	1250	17.4	43.4
Squash	133	1.9	4.6
Tomato	655	9.1	22.7
Total	2880	40.0	

Census of Agriculture[209] was used to calculate values of *n* for each fruit or vegetable. Estimated interception fractions for mature apples, snap beans, tomatoes, peaches, and cherries were calculated according to Eqs. (21) and (22) and weighted to derive a default interception fraction estimate of 0.052 for exposed produce (Table 3.3). Surprisingly, the values for the noncitrus fruits (apples, peaches, and cherries) are within approximately a factor of 1.3 of each other, and the values for the field crops are approximately equal to each other.

3.5 Correlation Between Interception Fraction and Standing Crop Biomass

As mentioned in Sect. 3.1, Chamberlain found a relationship between standing crop biomass or productivity and the interception fraction for pasture grasses. This relationship [Eq. (10)] is used in the TERRA code to calculate the interception fraction for pasture grasses and hay. The analyses of interception fraction for leafy vegetables, silage, and exposed produce (Sect. 3.2, 3.3, and 3.4, respectively) are based on generalized or average crops. Use of the interception fraction values for these categories as default estimates independent of complementary values of productivity (Y_i) could result in unreasonable overestimates of surface plant concentrations, c^{ps}, because

$$c^{ps} \propto \frac{r^i}{Y_i}. \tag{23}$$

That is, low values of Y_i coupled with values of r^i for average crops (represented by average Y_i values) could produce high values of r^i/Y_i. As Y_i approaches zero, the r^i/Y_i ratio approaches infinity.

Figure 3.3 indicates that leaf (or edible produce) surface area increases with time as the plant grows. Clearly, since interception fraction is proportional to surface area, the interception fraction for very young plants is less than that for mature plants, and r^i is a function of Y_i for the individual plant. However, it is not clear whether r^i is a function of Y_i for the mature plant in the field. Figure 3.5 illustrates the problem.

Figure 3.5 presents three plots of equal area with hypothetical crops represented by spheres. The relative ordering of productivity is A > B > C. In plots A and B planting geometry (packing) has been maximized (without staggering) by planting individual plants within a row and rows of plants adjacent to one another. The difference between the two crops is that the crop in plot A is of greater size (radius, r_f) than the crop in plot B. In plots B and C the crop radii are equal, but planting geometry is less efficient in plot C. In all plots the interception characteristics of the individual crops are equal.

It can be shown mathematically that the total surface area of crops in plots A and B are equal. That is, the decrease in surface area per plant as plant radius is reduced is exactly counterbalanced by the increase in number of plants per unit area. Therefore, the interception fraction for crops A and B should be the same. The productivity, however, is dependent on the volume multiplied by the number of plants per unit area. Since volume is proportional to the cube of plant radius, the productivity of plot A is greater than that of plot B. In this example, regardless of plant size the interception fraction is a constant value which is independent of productivity.

In plots B and C the interception fraction is a function of productivity. The surface area per plant is constant, and as planting geometry becomes less efficient, both productivity and interception fraction decrease porportionately.

The above examples illustrate that interception fraction for nongrasslike plants may or may not be a function of productivity, depending on whether a difference in productivity reflects a difference in plant size or a difference in plant spacings. This dilemma has been addressed in TERRA. As mentioned in the introduction to this report (and as will be discussed later), the TERRA code allows input of location-specific agricultural parameters, including location-specific productivity

Table 3.3. Values of the interception fraction for five important crops in the exposed produce category

Produce	r_l	r_f	n	l_f	Interception fraction	Weighting factor[a]
Apples	4.2 m	38 mm	10/m^2		0.034[b]	0.29
Snap beans		4 mm	220/m^2	55 mm	0.073[c]	0.21
Tomatoes		38 mm	20/m^2		0.068[b]	0.29
Peaches	1.8 m	31.8 mm	15/m^2		0.036[b]	0.14
Cherries	5.3 m	8.5 mm	160/m^2		0.027[b]	0.07
Weighted average					0.052	

[a]Based on values in Table 3.2.
[b]Eq.(21).
[c]0.75 × Eq. (22).

estimates. In TERRA the location-specific productivity estimate determines a corresponding interception fraction. In other words, it has been assumed that location-specific variations in productivity are more reflective of the differences in plots B and C than in A and B.

Since observed relationships between interception fraction and productivity are unavailable for nongrasslike plants, the relationship shown in Fig. 3.1 has been assumed to apply to nongrasslike plants also. The coefficients of the exponential terms for exposed produce, leafy vegetables, and silage have been determined by fitting an exponential regression equation, forced through the point $[(1-r^i = 0),(Y_i = 0)]$ to the points representing the United States average productivity-average interception fraction and maximum observed productivity-theoretical maximum interception fraction. The average and maximum productivities are taken from Appendices B and C of reference 7. The resulting relationships are (Fig. 3.6),

$$r^e = 1 - \exp(-0.0324 Y_e)\,, \tag{24}$$

$$r^{lv} = 1 - \exp(-0.0846 Y_{lv})\,, \text{ and} \tag{25}$$

$$r^s = 1 - \exp(-0.769 Y_s)\,, \tag{26}$$

where the superscripts and subscripts "*e*," "*lv*," and "*s*" are for exposed produce, leafy vegetables, and silage, respectively.

Although this approach is at best *ad hoc*, the consequences of setting the interception fraction at a constant value and allowing productivity to vary over its reported range are serious. Figure 3.7 compares the method of using Eqs. (24)-(26), case A, and using a single interception fraction, case B, over the observed productivity range shown at the bottom of the figure. At the extremes of the ranges, especially at productivities less than 0.1 kg/m^2, the ratio of r^i/Y_i is particularly suspect.

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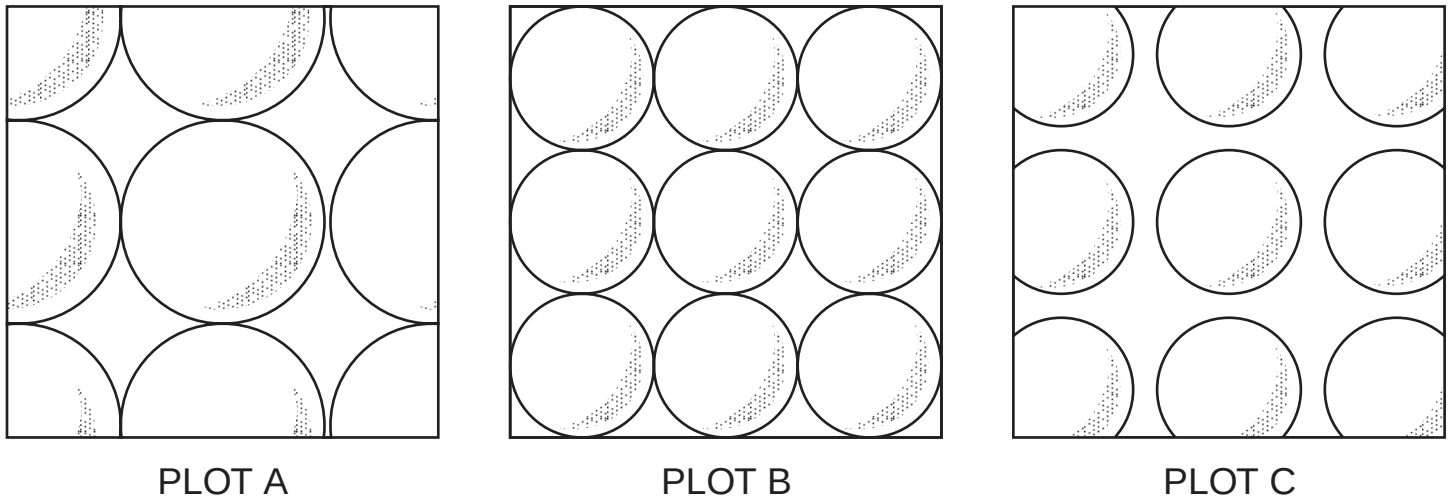

Figure 3.5. Three plots of equal area containing hypothetical crops of varying size and planting density.

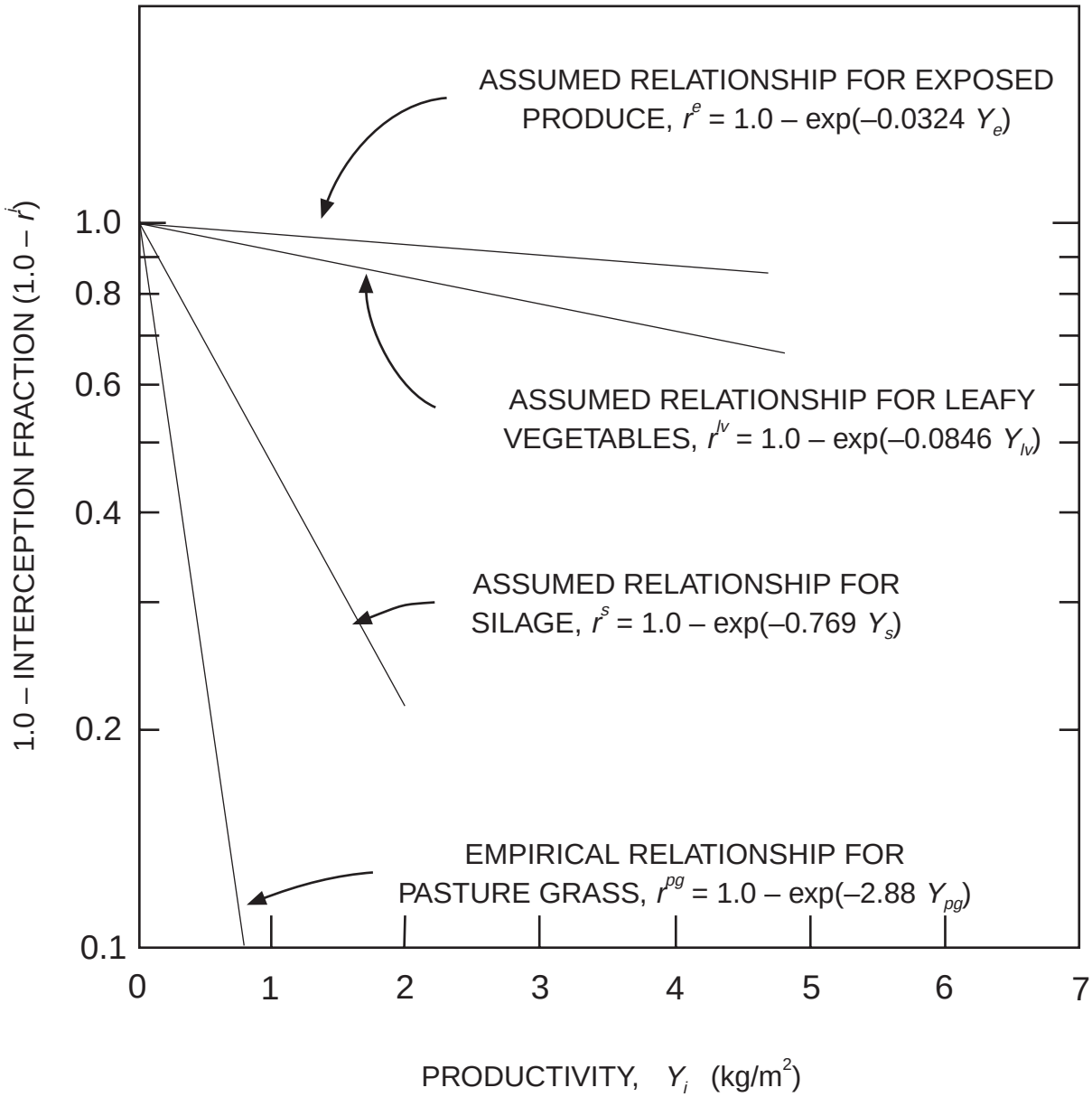

Figure 3.6. Assumed relationships between interception fraction and fresh weight productivity for exposed produce and leafy vegetables and between interception fraction and dry weight productivity for silage.

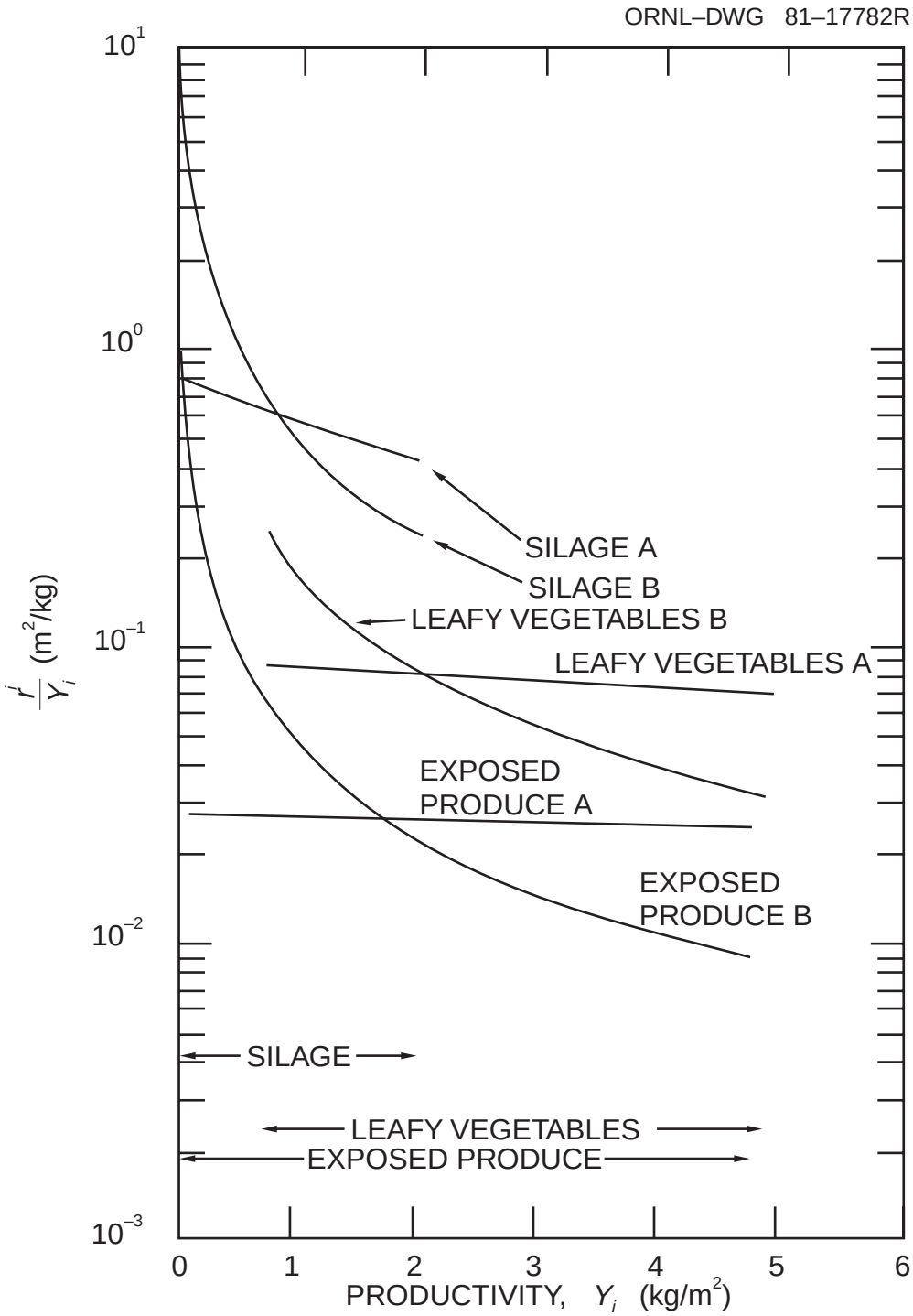

Figure 3.7. The ratio of interception fraction to productivity (r^i/Y_i) as a function of interception fraction dependent on (A) and independent of (B) productivity of silage, exposed produce, and leafy vegetables. The ranges of productivity found in the U.S., based on reference 7, are shown at the bottom of the figure.