Reviews

Root Piece Planting in Sweetpotato—A Synthesis of Previous Research and Directions for the Future

Nicholas A. George, Kenneth V. Pecota, Blake D. Bowen, Jonathan R. Schultheis, and G. Craig Yencho[1]

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SUMMARY. **Sweetpotato (*Ipomoea batatas*) is traditionally grown for fresh consumption, particularly in developed nations, but it is increasingly being used for alternative markets such as processed foods and industrial products. Sweetpotato is well suited for these end uses but its utilization is limited due to high production costs. These costs are primarily the result of high labor inputs. As a vegetatively propagated crop, sweetpotato is typically planted using unrooted plant cuttings, or "slips," which requires hand labor at several stages. Consequently, planting costs can be as high as 20% of total production costs. As an alternative to slips, sweetpotato can be established using root pieces, similar to the seed piece system used for potato (*Solanum tuberosum*). This system can be readily mechanized and therefore has the potential to reduce labor demands. Root piece planting has been investigated several times since the 1940s but is not reported to be in large-scale commercial use anywhere in the world. In this work, we review the research literature relating to root piece planting in sweetpotato. This literature demonstrates that it is possible for sweetpotato root pieces to produce yields comparable to slips, but that in most cases yields from root pieces are usually lower than from slips. We conclude that given suitable cultural management and appropriate varieties, it may be possible to successfully produce sweetpotato using root pieces. More work is necessary to develop root piece planting as a viable alternative to slips in sweetpotato production. This work should include the selection and breeding of adapted varieties, evaluation of the economics of sweetpotato production using root pieces, development of planting equipment suited to sweetpotato root pieces, and examination of chemical treatments to improve success of root piece planting.**

Sweetpotato is one of the world's most important and widely grown starchy crops, with annual production in over 110 countries currently estimated to total 114 million tonnes (Food and Agriculture Organization of the United Nations, 2010). In developed nations, sweetpotato is primarily grown for fresh consumption or as a canned product, but the markets for sweetpotato as a value-added processed food and bio-based industrial products are growing. For example, sales of processed sweetpotato in the United States increased by an average of 20,000 lb per year during 2007–09, to a total close to 110,000 lb in 2009 (U.S. Sweet Potato Council, 2011). Sweetpotato can also produce large yields of biomass suitable for conversion to industrial products (Ziska et al., 2009). For example, the starch can be converted to simple sugars and then used to produce plastics or fuels, such as ethanol and butanol (Klass, 1998).

In all parts of the world sweetpotato crops are propagated using unrooted sprouts or vine cuttings (Loebenstein and Thottappilly, 2009). Sweetpotato is a perennial species but can only be grown year-round in tropical and subtropical climates. In these climates, vine cuttings are taken from existing crops. Sweetpotato can be grown successfully in temperate regions, but only as a summer annual. In temperate regions, sweetpotato roots are stored over winter, bedded in early spring, and the sprouts from these roots, known as "slips," are then used for propagation.

Propagation of sweetpotato crops from slips in temperate regions is demanding in terms of time, expense, and labor. The "seed" roots must be over wintered, which incur storage costs. Large field crews are then required for manual bedding of roots, cutting of slips, and transplanting. In the United States, estimates of the total production costs of sweetpotato range from $1800/acre to $3400/acre, with slip production and planting being 15% to 20% of this (Estes et al., 2002; Hinson and Boudreaux, 2007; Martin et al., 2000; Mississippi State University, 2007).

As alternative end uses of sweetpotato are developed, the need to make production less costly and labor intensive becomes more important. An alternative to propagating sweetpotato with slips is to use small roots or, more commonly, pieces of roots.

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Department of Horticultural Science, North Carolina State University, 214 Kilgore Hall, Campus Box 7609, Raleigh, NC 27695

[1]Corresponding author. E-mail: Craig_Yencho@ncsu.edu.

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.4536	lb	kg	2.2046
28.3495	oz	g	0.0353
0.9072	ton(s)	t	1.1023

This is similar to the propagation system used for potato and is also called "seed piece planting" or "direct planting." As is the case for potato, this method of propagation lends itself to mechanization, and therefore reduces labor requirements.

Root piece planting in sweetpotato has been investigated since the 1940s but is not reported to be used commercially anywhere in the world. In this work, we review and synthesize the research literature relating to root piece planting in sweetpotato, assess the potential of root piece planting as a viable alternative to slips, and make recommendations for future research.

Overview of root piece research

There is a 70-year history of published research relating to propagating sweetpotato using root pieces (Table 1). The research was primarily conducted in Japan and the United States, with the only sustained research effort undertaken by workers in Japan between the 1950s and 1970s, and the chronology in Table 1 shows that the majority of the research ceased after the 1980s. Much of the research is also reported in the "gray literature," obscure journals, brief conference abstracts or remains unpublished, making it challenging to thoroughly review the work. English translations of earlier Japanese research are also not always available, making it difficult for international researchers to access. Additionally, except for summaries of Japanese work before the 1970s (Ikemoto, 1971; Kobayashi, 1968), there has been no prior attempt to provide a comprehensive overview and synthesis of sweetpotato root piece research.

Perhaps as a consequence of this publication history, the body of research on sweetpotato root piece planting is frequently repetitive. For example, independent studies on the effects of seed piece size on the success of root piece planting were conducted in 1943, 1946, 1954, 1962, 1969, and 1982, all reaching effectively similar conclusions (Georgia Coastal Plain Experimental Station, 1943; Kays and Stutte, 1982; Kodoma, 1962; Kodoma et al., 1954b; Lutz et al., 1946; Nakazawa and Sano, 1969), and yet the present authors are aware of contemporary researchers examining root piece size effects. Such duplication could be avoided if previous research were more accessible. One of the prime motivations for this review is therefore to synthesize the state of knowledge regarding root piece planting in sweetpotato so as to make the findings more readily available and to foster future research.

Despite the repetition in the literature, several important themes relating to sweetpotato establishment from root pieces can be identified. These include the common problems experienced when planting root pieces and the influences of cultural management and genetic factors in overcoming these problems. These will be explored throughout the remainder of the review.

We also to wish to note that the present authors began research relating to sweetpotato root piece planting in the early 2000s. This work has included both cultural management studies and germplasm screening. The cultural management work involved studies of the effect of root piece, planting date, root piece size, and the effect of ethylene on root piece sizing and rotting. Breeding work has included germplasm screening and an investigation of the heritability of traits associated with root piece planting. This work is either in preparation for publication or on going.

Root type nomenclature

When grown from root pieces, sweetpotato can produce a number of different storage root types. Figure 1 depicts and summarizes the most common nomenclature used for storage roots arising from a root piece. "Mother pieces" result from the enlargement of the smaller planted root piece. Any new storage roots produced, aside from the mother piece, are termed "daughter roots." Daughter roots are typically divided into two classes: "direct daughter roots," produced directly from the planted mother piece, and "indirect daughter roots," produced from adventitious sprouts derived from the mother root. We recognize two further categories of storage roots, "enlarged sprouts" and "semi-indirect daughter roots." Enlarged sprouts arise from the thickening of adventitious sprouts that emerge from the planted root pieces. Semi-indirect daughter roots form from adventitious roots that emerge from the enlarged sprouts. Sweetpotato clones vary in the number and types of these root types that they produce. To aid in germplasm selection, Bouwkamp (1982) proposed a classification system to describe these different types and used this system to inform their selection activities (Fig. 2). The system categorized clones as producing direct daughter roots, indirect daughter roots, or no daughter roots, and within each of these categories as having mother pieces that enlarge, do not enlarge, or rot. These categories are nondiscrete, with intermediate types present, especially in terms of the extent of mother piece sizing (Bouwkamp, 1982).

Common problems encountered from root piece planting

Root piece planting can occasionally produce root yields and root quality comparable to slips, but most workers report that for the same clone yields and root quality from root pieces are generally inferior than from slips. Five, interrelated, factors are primarily responsible for sweetpotato root piece planting being less successful than planting with slips:

1) **Lower yields from root pieces than slips.** Most studies report that total yields tend to be greater when a sweetpotato clone is established from slips rather than from root pieces. For example, Lutz et al. (1946) found that yields from root pieces for two clones were on average 59% that of slips. A recent 3-year study comparing several clones at two sites in North Carolina found the yield from root pieces was on average 49% lower than the yield from slips (Bowen, 2010). However, some workers have identified clones where slips and root pieces produce comparable yields. For example, Bouwkamp (1982) selected three clones which produced yields from root pieces that were within 5% of the same clones planted as slips.

2) **Root piece enlargement.** Planted root pieces of sweetpotato regularly become a sink for photoassimilates and enlarge. In some cases, the enlarged mother pieces comprise most, or all, of the harvested storage root yield. The enlargement of the planted piece is undesirable because the mother piece tends to be deformed and cracked. This results in an increased propensity for rotting and severely limits the usefulness of mother pieces. Kodoma (1962) proposed that root piece enlargement may also directly reduce the production of daughter roots because the mother pieces

Table 1. A chronology and summary of the main research literature relating to the use of root piece planting in sweetpotato.

Reference	Location	Summary
Georgia Coastal Plain Experimental Station (1943)	United States	Examined effect of variety, planting times, soil types, seed piece size, planting rates, presprouting, fungicides, and the production of root piece material on root piece planting
Hidaka (1946)	Japan	In Japanese. No English summary. Title—Some experiments on the method of reusing seed roots of sweetpotatoes
Lutz et al. (1946)	United States	Examined the effect of varieties, planting times, soil types, seed piece size, cutting of seed pieces, and fungicides on root piece planting
Kiyono (1946)	Japan	In Japanese. No English summary. Title—Direct planting method by small roots of sweetpotatoes
Kodoma and Kobayashi (1952)	Japan	Compared growth habits of plants derived from root pieces and slips, also studied planting times
Kodoma et al. (1954a)	Japan	Compared growth habits of plants derived from root pieces and slips
Kodoma et al. (1954b)	Japan	Investigated methods for producing roots to be used for root piece planting, also examined variety differences and planting times
Kodoma and Nomoto (1955)	Japan	Compared the productivity of root piece planting under different nutrient regimes, soil temperatures, and moisture contents
Kodoma et al. (1958)	Japan	Compared the productivity of root piece planting under different soil types and moisture contents
Akita and Kobayashi (1962)	Japan	Studied the effect of temperature, light, and soil moisture on the extent of mother piece enlargement
Shirasaka and Sakai (1962)	Japan	In Japanese. No English summary. Title—Studies on characters of sweetpotatoes varieties. I. Adaptability for direct planting
Akita et al. (1962a)	Japan	Examined the physiological changes of seed pieces when exposed to sunlight
Kodoma (1962)	Japan	Compared the growth habits of plants derived from root pieces and slips. Also examined the effects of varieties, soil moisture, soil type, seed piece size, planting depth, planting times on the productivity root piece planting. The physiological effects of sunlight on root pieces were studied. Germplasm adapted to direct planting was selected
Akita and Ono (1965)	Japan	In Japanese. No English summary. Title—On the combining ability in sweetpotato breeding for the seed tuber planting culture
Kobayashi and Akita (1965)	Japan	In Japanese. No English summary. Title—Characteristics of tuber development in sweetpotato by seed tuber planting culture
Akita and Kobayashi (1965)	Japan	Germplasm was screened for root piece planting ability
Kobayashi and Akita (1966)	Japan	In Japanese. No English summary. Title—Studies on the breeding of sweetpotato adapted for the seedtuber planting culture. I. Variations of yielding ability in F-1 plants
Fujise (1966)	Japan	In Japanese. No English summary. Title—Comment of experimental studies on sweetpotato and potato breeding in Japan
Kobayashi (1968)	Japan	Summarized previous Japanese research. Studied growth habits of root pieces vs. slips. Examined the effect of planting depth. Conducted grafting studies between adapted and nonadapted germplasms. Screened germplasm for adapted varieties
Nakazawa and Sano (1969)	Japan	Studied the effect of seed piece size, cutting and root piece age on the extent of mother piece sizing
Kobayashi et al. (1969)	Japan	Examined yield stability of adapted and unadapted varieties when planted as root pieces
Harmon (1970)	United States	Conference abstract stating that cultural management studies and germplasm selection took place, no details provided
Ikemoto (1971)	Japan	Summarizes ideal cultural management practices for root piece planting based on previous Japanese studies
Bouwkamp et al. (1971)	United States	Investigated ways to promote sprouting from root pieces including presprouting, cutting, and fungicides. Also observes that varietal differences in exist
Bouwkamp and Scott (1972)	United States	Comparison of yield between direct and slip-planted sweetpotato clones
Kusuhara et al. (1972)	Japan	Determined the heritability of traits important for root piece planting
Nakazawa (1973)	Japan	Investigated the use of different presprouting conditions to promote sprouting from cut root pieces

(*Continued on next page*)

Table 1. (*Continued*) A chronology and summary of the main research literature relating to the use of root piece planting in sweetpotato.

Reference	Location	Summary
Tompkins and Horton (1974)	United States	Investigated the use of ethylene for promoting the sprouting of root pieces
Shikata et al. (1975)	Japan	A report on the release of the first sweetpotato variety developed specifically for seed piece planting
Hozyo and Kato (1976)	Japan	Examined of the effects of exposing root pieces to light
Allen and Phills (1979)	United States	Conference abstract. Examined effect of different varieties and cutting on root piece planting
Phills and Allen (1979)	United States	Conference abstract. Germplasm was screened for root piece planting ability
Kays and Stutte (1982)	United States	Examined the effect of cutting of root pieces and root piece size on the outcome of root piece planting
Bouwkamp (1982)	United States	Examined the effect of presprouting treatments and fungicide on root piece planting. Describe selection methodology for varieties adapted to root piece planting
Jeong et al. (1986)	Korea	Compared the effect of different nutrient regimes and planting times
Hosokawa et al. (1998)	Japan	Built and tested a self-propelled semiautomatic seed piece planter
Yamashita (2000)	Japan	Studied the effect of different hormone treatments on the sprouting and root growth of root pieces
Kubota et al. (2000)	Japan	Compared time and cost saving between planting systems using root pieces and slips
Arima et al. (2002)	Japan	Studied the effect of different hormone treatments on the sprouting and root growth of root pieces
Bowen (2010)	United States	Examined the effect of cutting on sprouting and yield from root pieces and estimated the heritability of traits important to root piece planting

will compete with daughter roots for photoassimilates. However, research at North Carolina State University has found no correlation between mother piece size and daughter root yield (Bowen, 2010), so the importance of root piece enlargement to the yield of daughter roots is uncertain.

3) **Reduced stand establishment from root pieces.** Reduced stand establishment is a problem in root piece planting compared with transplanted slips. For example, early work found that slips displayed on average 85% survival, whereas root pieces achieved on average 36% (Lutz et al., 1946). Reduced plant stands can also lead to higher weed density, further decreasing yield (Bouwkamp, 1982). Reduced stand establishment is thought to be due primarily to the rotting of the root piece in the soil before sprouting. As will be discussed, cutting roots of seed roots is often used to both increase root piece number and to promote sprouting from the distal end of the root. This practice increases the risk of rot by providing an entry point for pathogens, typically soft rot (*Rhizopus* sp.) (Bouwkamp et al., 1971).

4) **Inferior daughter root appearance.** For most sweetpotato clones, the physical characteristics of daughter roots produced from a planted root piece are usually inferior when compared with roots produced from transplanted slips (Bouwkamp, 1982; Georgia Coastal Plain Experimental

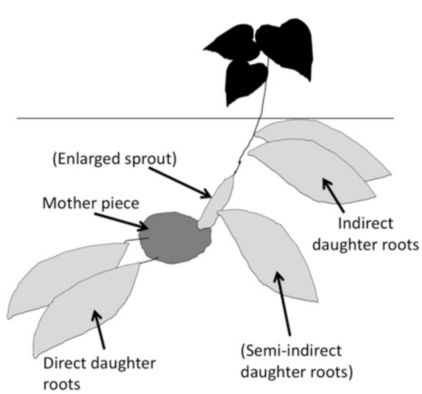

Fig. 1. Sweetpotato root types derived from root piece planting (Kobayashi, 1968); types in parentheses are recognized by the North Carolina State University research group.

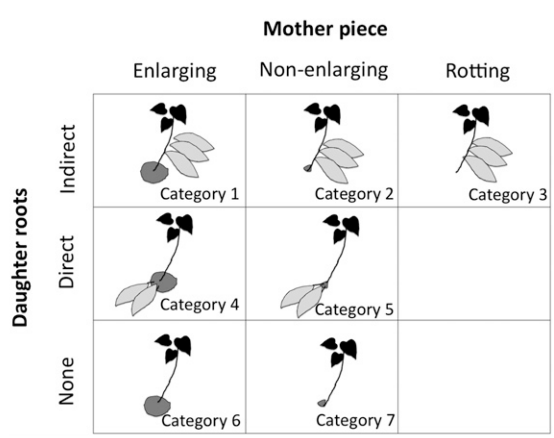

Fig. 2. Sweetpotato plant type classification system derived from root piece planting: 1) indirect daughter root piece enlarging, 2) indirect daughter root piece remaining, but not enlarging, 3) indirect daughter root piece disappearing, 4) direct daughter root piece enlarging, 5) direct daughter root piece remaining, and 6) mother piece enlarging with no to very few daughter roots (Bouwkamp, 1982). Note that these are nondiscrete categories.

Station, 1943; Kobayashi, 1968). Daughter roots produced from root pieces tend to be relatively more misshapen and have rougher skin. Kobayashi (1968) observed that it was direct daughter roots that tend to be misshapen, rather than indirect roots. Our research group has also observed that semidirect roots appear inferior to indirect roots.

5) Reduced yield stability. Reliable data regarding yield stability are not widely published, but researchers at the Chugoku Agricultural Experimental Station state that the annual yield stability from clones planted as root pieces is usually less than for the same clones planted as slips (Kobayashi, 1968; Kobayashi et al., 1969).

These five interrelated factors provide a framework for reviewing literature with respect to root piece research throughout the remainder of the review.

The influence of cultural and genetic factors on root piece planting

Research literature shows that the outcome of root piece planting is influenced by both environmental and genetic factors (Allen and Phills, 1979; Georgia Coastal Plain Experimental Station, 1943; Kobayashi, 1968; Kodoma, 1962; Lutz et al., 1946; Nakazawa, 1973; Nakazawa and Sano, 1969; Phills and Allen, 1979). The following sections address the influence of both cultural and genetic factors on the problems described above.

Cultural factors

Researchers have widely investigated the use of basic cultural management to address the problems associated with root piece planting. The earliest published research relating to root piece planting in sweetpotato addresses different cultural practices in an attempt to rectify problems associated with planting sweetpotato from root pieces (Georgia Coastal Plain Experimental Station, 1943; Kiyono, 1946; Kodoma, 1962; Kodoma and Kobayashi, 1952; Kodoma et al., 1954a, 1954b, 1958; Kodoma and Nomoto, 1955; Lutz et al., 1946; Nakazawa, 1973; Nakazawa and Sano, 1969). This work generally targeted the problem of root piece enlargement and poor daughter root yield. The cultural factors identified as having the greatest role in dictating the extent of daughter root yield and root piece enlargement were the size of the planted root piece and soil type.

There is a strong positive correlation between the size of a sweetpotato root piece and the extent to which it enlarges; smaller pieces result in reduced enlargement (Kodoma, 1962; Nakazawa, 1973; Nakazawa and Sano, 1969). Smaller root pieces also exhibit reduced sprouting relative to larger ones though (Takatori, 1961; Yamashita, 2000), so smaller roots are prone to reduced stand establishment. So a tradeoff exists between planting a root piece small enough to minimize enlargement but large enough to allow sufficient sprouting for establishment. The ideal root piece size appears to vary between varieties, but is ≈40 to 60 g (Kodoma, 1962; Yamashita, 2000), although some workers report success with pieces of around 20 g under field conditions (Bouwkamp, 1982).

Planting on coarser soils results in greater daughter root yield and less enlargement of root pieces than planting on fine textured soils (Georgia Coastal Plain Experimental Station, 1943; Kodoma, 1962; Lutz et al., 1946; Nakazawa, 1973; Nakazawa and Sano, 1969). The underlying mechanism for this effect is unknown and requires investigation, but we propose that there are two possible causes: First, coarser soils are likely to be drier, therefore the root piece acts as source of moisture for aboveground biomass; second, soil moisture dictates whether primordia become roots or shoots, with shoots predominating in drier conditions (Yasui, 1944). Therefore in drier soil more adventitious shoots are produced which may lead to the production of more indirect daughter roots.

Other factors, such as planting date, soil temperature and moisture, and planting depth, influence root piece planting but their effect varies considerably between varieties, seasons, and sites (Kobayashi, 1968; Kodoma, 1962). Generalizations regarding the impact of these cultural practices therefore cannot be made readily. Unpublished research from our root piece studies show a low consistency in ranking of clones between years and sites. We hypothesize that variation reported by other workers may be indicative of genotype by environment interaction.

Interestingly, Japanese researchers found that removing soil from previously planted root pieces completely inhibited mother piece sizing and resulted in the development of daughter root yields that were comparable to using slips (Kodoma, 1962). This is called the "sun exposure" planting method. The effect is independent of the sweetpotato clone used (Kodoma, 1962). The underlying reason for the failure of mother roots to enlarge when uncovered was found to be epidermal thickening and lignification caused by sunlight exposure (Akita and Kobayashi, 1962; Akita et al., 1962a). The sun exposure method is probably not a viable cultural management technique because uncovering planted root pieces on a field scale would pose practical challenges and increase the risk of pest damage. The findings do suggest however that if epidermal thickening and lignification can be induced by other means, such as via chemical treatment, or breeding, mother piece sizing may be reduced.

Reduced stand establishment is also a major problem associated with root piece planting in sweetpotato. The early studies in the United States concluded that both inferior sprouting and rotting of the planted piece were the primary determinants of reduced stand establishment and recommended presprouting the pieces to promote sprouting and using fungicides to prevent rotting (Georgia Coastal Plain Experimental Station, 1943; Lutz et al., 1946). During the 1970s and early 1980s, the University of Maryland confirmed that rotting of pieces in-ground before sprouting is the primary reason for reduced stands and began more comprehensive examination of methods to reduce rotting and increase sprouting of planted root pieces (Bouwkamp, 1982; Bouwkamp and Scott, 1972; Bouwkamp et al., 1971; Kays and Stutte, 1982). Presprouting at elevated temperature and humidity, similar to what is done to sweetpotato roots before bedding, was reported to result in greater sprouting and yields compared with roots that were not presprouted. For example, relative to the control, 5 weeks of presprouting increased total emergence by 34% and marketable yield by 35%, although the yield difference was not statistically significant (Bouwkamp, 1982). The use of the fungicide dicloran also effectively reduced rotting during presprouting and after planting (Bouwkamp et al., 1971). The magnitude of the response to fungicide varied between clones, suggesting the propensity for rotting before sprouting, and the extent of sprouting may be influenced by genetic factors (Bouwkamp, 1982; Bouwkamp et al., 1971). Note that another tradeoff exists here since the rotting of the piece after planting is desirable because it eliminates mother piece sizing.

In potato, seed tubers are cut into pieces to increase propagation material. Cutting sweetpotato storage roots does not have a significant or consistent effect on yield of daughter roots (Bowen, 2010; Kays and Stutte, 1982; Lutz et al., 1946). Sweetpotato storage roots typically exhibit a strong apical dominance so cutting of storage roots will break apical dominance and increase the number of sprouts produced by the distal end of the root (Kays and Stutte, 1982; Takatori, 1961). This allows both the apical and distal pieces to be used for planting. In general, it appears that cutting roots to produce more seed for planting will not have a detrimental effect on yield from root piece planting if a fungicide is used to reduce root piece rotting.

The use of plant hormones as a method to promote sprouting and root growth of planted root pieces has been investigated (Arima et al., 2002; Yamashita, 2000). Yamashita (2000) explored the use of a number of common plant hormones on small (1 to 10 g) sweetpotato root pieces and found that, relative to controls, rooting was increased significantly, from 0% to 50% of pieces, after treatment with 100 $mg \cdot L^{-1}$ indole-3-acetic acid, and shoot growth was increased 2.8 times relative to controls with 5 $mg \cdot L^{-1}$ abscisic acid. Yields of storage roots from treated pieces in this work were comparable to the yield obtained from slips. Ethephon, an ethylene delivery chemical, has also been investigated as a means to induce sprouting of root pieces (Tompkins and Horton, 1973). These workers found that root pieces soaked in 1000 ppm of ethephon for 10 min displayed on average 50% greater emergence and 34% greater yields than untreated controls. In addition, the researchers reported that many root pieces treated with ethephon failed to enlarge although they do not provide details. Continuing investigations of ethephon by our research group have found similar results. Hormone treatments may therefore provide a way to facilitate root piece planting in sweetpotato and warrant further investigation.

The above discussion indicates that a number of cultural management practices can improve the outcome of root piece planting. However, these improvements are most successful in terms of reducing enlargement of mother pieces and improving stand establishment. The ability to consistently increase yield, appearance, and yield stability is minimal. Cultural methods therefore cannot completely eliminate the problems inherent with root piece planting. Many studies report variation between clones in terms of adaption to root piece planting (Akita and Kobayashi, 1962; Bouwkamp and Scott, 1972; Georgia Coastal Plain Experimental Station, 1943; Kodoma, 1962; Kodoma et al., 1954b; Lutz et al., 1946; Phills and Allen, 1979; Shirasaka and Sakai, 1962). The ultimate success of root piece planting is likely to be determined by a combination of cultural practices and the selection of appropriate clones.

Genetic factors

In a diverse collection of germplasm, sweetpotato clones that produce a high daughter root yield and low mother piece sizing when planted from root pieces can typically be found, albeit at a low rate. One way to demonstrate this is to examine "partitioning index." Partitioning index provides a measure of the partitioning of yield between daughter roots and enlarged root pieces [partitioning index = (daughter root yield − mother piece yield) ÷ total yield]. The value varies from 1.00 to –1.00. A value of 1.00 indicates all yield is daughter roots, –1.00 all yield is root pieces, and 0.00 the yield is evenly divided between the two. Data for two diverse populations show that clones exist with a range of partitioning indexes. About 1% of clones have partitioning indices of 0.9 or greater (Fig. 3). The heritability (h^2) of the partitioning index is estimated to be relatively high [h^2 = 0.4 to 0.6 (Bowen, 2010)], suggesting it should be possible to select and breed for clones with high partitioning indexes. This would overcome low daughter root yield and mother piece enlargement, two of the main problems associated with root piece planting.

Yield in sweetpotato transplanted from slips is reported to be heritable [h^2 = 0.7 (Jones, 1986)], however daughter root yield from root pieces was found not to be heritable [h^2 = 0.0 (Bowen, 2010)]. This would appear

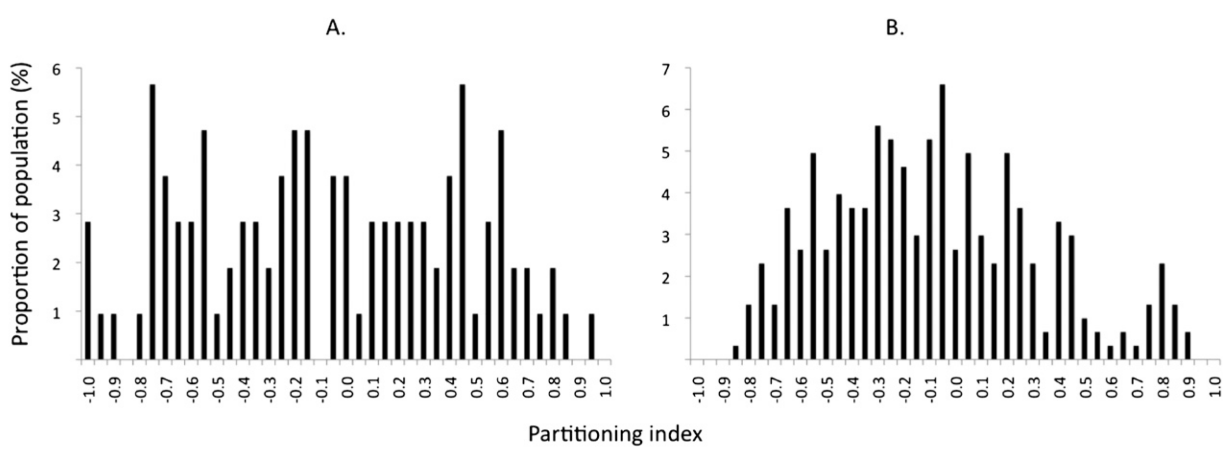

Fig. 3. The occurrence of sweetpotato clones with different rooting types: (A) 106 randomly selected clones (Kobayashi, 1968); (B) 304 clones from a segregating population (Bowen, 2010). Partitioning index provides a measure of the partitioning of yield between daughter roots and enlarged root pieces [partitioning index = (daughter root yield − mother piece yield) ÷ total yield].

to contradict the finding that partitioning index is heritable given the value is related to daughter root yield. The reason for these discrepancies are unknown and further investigation is required to determine if breeding can be used to address the problem of yield stability in root piece planting. Related to this, it has been hypothesized that root piece enlargement directly reduces the production of daughter roots (Kodoma, 1962). Reducing root piece sizing would therefore need to be one of the primary objectives of both breeding and cultural work (Kodoma, 1962). However, an examination of data from Bowen (2010) contradicts this, finding only a very weak relationship between yield of daughter roots and partitioning index (Fig. 4). High-yielding clones will therefore not necessarily produce low yields of enlarged mother pieces. These results suggest that high daughter root yield and low mother piece enlargement may need to be selected for separately, and that it could be difficult to breed directly for higher yields.

Variation in root piece sprouting between sweetpotato clones has been observed, and heritability of sprouting is reported to be low to moderate [h^2 = 0.4 (Jones, 1986)]. This suggests that clones with greater seed piece sprouting ability could be developed. However, steps would need to be taken to also avoid sprouting while in storage. Furthermore, Bouwkamp (1982) reported a moderate correlation between clones that fail to exhibit mother piece sizing and those that produce few or less vigorous sprouts. A correlation between these traits would mean that the selection of varieties with high partitioning indices could indirectly select for reduced stand establishment. Examination of data from North Carolina State University field trials did not find a relationship between sizing and sprouting. The nature of this relationship will therefore need to be investigated further.

Relative to direct root types, indirect root types in sweetpotato tend to have a superior appearance and possibly greater yield stability (Kobayashi, 1968). Selecting for clones that produce primarily indirect daughter roots would therefore address problems of inferior daughter root appearance and low yield stability associated with root piece planting. The proportion of clones from a random selection of germplasm that will produce predominantly indirect daughter roots is not published. Nevertheless, indirect daughter root production has been found to have a relatively high heritability (h^2 = 0.54) and direct daughter root types are moderate (h^2 = 0.29) (Kusuhara et al., 1972). It should, therefore, be feasible to develop clones with superior appearance and greater yield stability by selecting and breeding for indirect root types.

Japanese efforts demonstrate the feasibility of developing sweetpotato clones adapted to root piece planting via selection and breeding. The Chugoku Agricultural Experimental Station began work to develop clones for root piece planting in 1956 (Kobayashi, 1968). The program screened for root piece planting ability in the second selection cycle, after making an initial selection for varieties with suitable agronomic and quality characters in the first year. This work led to the selection of the clone ‘Naeshirazu’, a white-fleshed, indirect daughter type that produces large numbers of small roots which can be used as seed and only requires 4 weeks to sprout following planting (Shikata et al., 1975). It was intended for the production of starch and livestock feed. ‘Naeshirazu’ was released as a commercial variety but was never produced commercially. In 2011, the National Agricultural Research Center for Kyushu Okinawa Region, Japan, released the variety Tamaakane (Sakai et al., 2011), an orange-fleshed clone intended for fermentation for liquor that can also be planted via root pieces.

Development of sweetpotato clones adapted to root piece planting can therefore be achieved by including a screening component for root piece planting characteristics into breeding programs. An evaluation of root piece planting characteristics can be included in the second year of screening, after clones have first been screened for desirable agronomic traits and suitability for target end uses. The breeding program at North Carolina State University has adopted this approach. Screening for root piece planting ability can be conducted by planting clones as root pieces and selecting those clones which display high yield and partitioning index, indirect daughter root production, and good sprouting. Given the moderate to high heritability of most traits of interest, development of a recurrent selection program for seed piece planting characteristics should lead to an increase in the adaption of breeding populations to root piece planting over time.

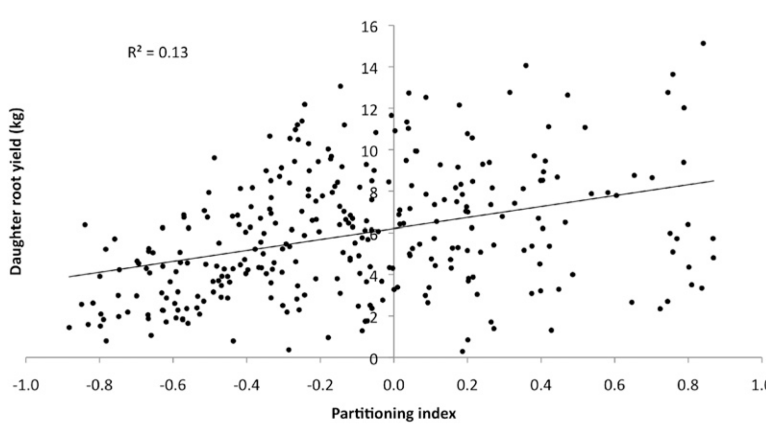

Fig. 4. The relationship between daughter root yield and partitioning index in sweetpotato (Bowen, 2010); partitioning index = (daughter root yield − mother piece yield) ÷ total yield; 1 kg = 2.2046 lb.

Conclusions and recommendations for future work

Research literature and the experience of Japanese breeders suggests, given the development of suitable clones and use of appropriate cultural management methods, it should be possible for root piece planting to be used as a viable alternative to slip in sweetpotato. Root piece planting could be particularly useful where root appearance is less critical and could therefore provide an avenue for reducing production costs and permit the economical production of sweetpotato for processed food and industrial end uses.

It is unclear from the literature if it is possible to develop clones that produce roots with reasonable appearance and size ranges to make them suitable for tablestock markets.

Future work is required to facilitate the development of root piece planting as a commercially viable method of planting sweetpotato. This work should include:

1) Examination of the heritability of traits that will affect the outcome of root piece planting. Breeding efforts for sweetpotato clones adapted to root piece planting will be aided by further heritability studies, particularly of daughter root yield and sprouting ability. There are conflicting reports regarding the correlation between some traits of interest so examination of the nature of the relationship between traits of interest is needed.

2) The further examination of plant hormones and other chemical treatments. The promising results from studies of plant hormones suggest these or other chemical treatments may be used to induce sprouting and rooting of pieces while facilitating epidermal thickening, lignification, rotting, or both of the planted piece. Further evaluation of plant hormones and other chemicals as tools in root piece planting is needed.

3) Examination of the developmental physiology and morphology of daughter roots in root piece planting. There is little published work examining the underlying mechanisms responsible for the success or failure of individual sweetpotato clones when planted as root pieces. Understanding the developmental physiology and morphology of storage roots in sweetpotato has been useful for indentifying the relationship between root anatomy and yield of sweetpotato storage roots (Belehu et al., 2004; Togari, 1950; Wilson and Lowe, 1973), but investigations of this type have not been conducted for root pieces. Such studies would be useful to facilitate a better understanding of the results of both cultural management and breeding studies relating to root piece planting.

4) Examination of the practicality of root piece planting in sweetpotato. It is assumed that root piece planting used for potato can also be incorporated into sweetpotato production systems, but little work has be done to demonstrate this. For example, it is unclear whether adapting equipment for root piece production and planting in potato for use in sweetpotato is feasible. It is also unclear whether the lower rate of vegetative increase from root pieces vs. slips will make root piece planting feasible. Investigations of the practical issues surrounding the use of root piece planting in commercial sweetpotato production systems should be conducted.

5) Economic analysis of sweetpotato root piece planting. There is little published work estimating the potential time and economic savings root piece planting may provide over conventional sweetpotato production systems in terms of labor inputs, crop and seed increase potential and ultimately, profitability. A single Japanese study concluded the root piece planting provided little cost and time saving benefits relative to slips (Kubota et al., 2000). Further analysis of this type will be necessary for both guiding and providing justification for cut root piece research in sweetpotato in the future.

New markets for sweetpotato are developing, but their viability will require lower cost production systems. Root piece planting is readily mechanized and could reduce a large cost component of production by reducing labor demands. A 70-year body of work demonstrates that root piece planting in sweetpotato can be as successful as planting from slips under some circumstances, but that a range of problems must be overcome before it can be reliably used for commercial production.

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