Grafting Manual:
How to Produce Grafted Vegetable Plants

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Synopsis:
Vegetable grafting creates a new plant by combining two plants with different genetic background, with one (scion) providing the shoots and the other the roots (rootstock), combining the desirable traits of both.

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USDA United States Department of Agriculture National Institute of Food and Agriculture

Why Graft?

The practice of grafting used in vegetable production is similar to fruit tree grafting in that it creates a new plant by physically combining two plants with different genetic background, with one providing the shoots (scion) and the other donating the roots (rootstock). When the two genotypes are compatible, their vascular bundles reconnect at the graft union, where the wounded surfaces of the scion and rootstock meet, without presenting a barrier for water and nutrient translocation (Fig. 1). Despite the relatively high cost of grafted transplants, due to increased labor and input for producing them, as compared to regular (non-grafted) transplants, grafting has evolved into a unique cultural practice that helps reduce pesticide use, enhances yield and production efficiency, and improves economic viability in sustainable vegetable production under both open field and

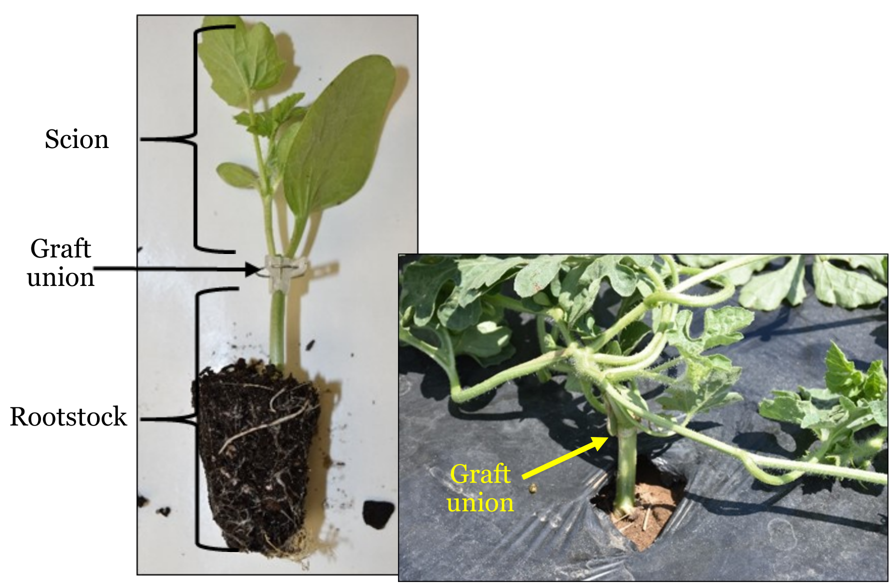

Figure 1. Grafted watermelon transplant ready for transplanting (left) and grafted watermelon grown in plastic-mulched raised bed in an open-field system (right). *(Photos by Michele Colaluce and Xin Zhao)*

protected culture systems (Lee et al., 2010; Kubota et al., 2008). Figure 2 illustrates a general concept of using grafted plants to benefit vegetable production by obtaining desirable traits from scion and rootstock cultivars, which are not only determined by the intrinsic characteristics of scions and rootstocks but also their interactions as well as the environmental conditions.

Grafting as an IPM tool for disease management – complementary to standard disease resistance breeding of new cultivars

At present, vegetable grafting is mainly applied to solanaceous and cucurbitaceous crops, primarily tomato, eggplant, pepper, watermelon, cucumber, and melon. Although some growers may still prefer to graft their own transplants, it is becoming more common to source desirable grafted seedlings from commercial nurseries (Fig. 3). Grafting is an effective IPM (integrated pest management) tool for managing soilborne diseases, which was the primary purpose for the development of vegetable grafting, and continues to be one of the main purposes for its use today (Guan et al., 2012; Louws et al., 2010). In the search for alternatives to methyl bromide, the role of grafting with resistant or tolerant

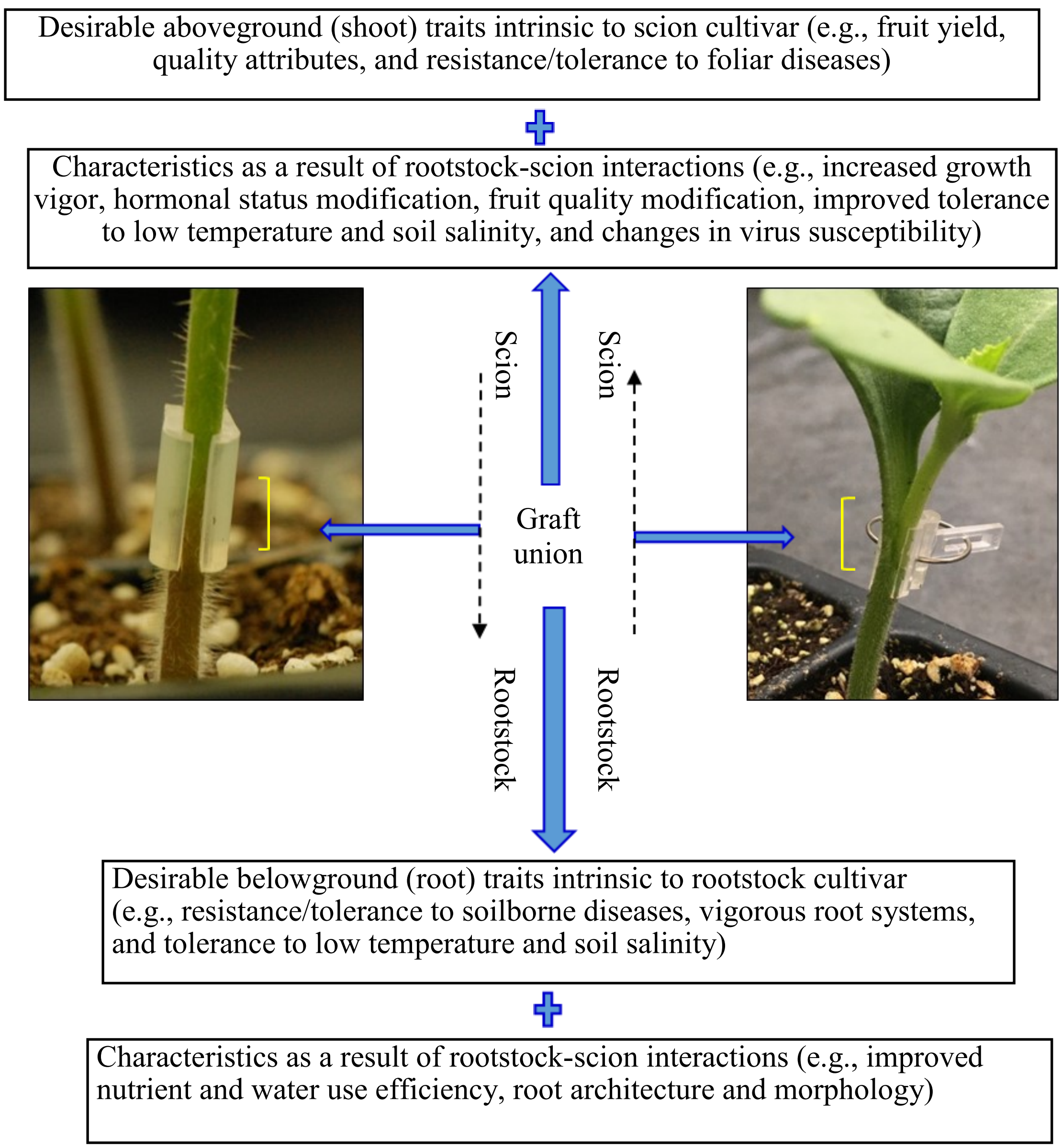

Figure 2. An illustration of a general concept of vegetable grafting *(Photos by Xin Zhao)*.

rootstocks is recognized as an environmentally-friendly approach to control soilborne pests in addition to other cultural strategies that include resistant cultivars, crop rotation, and biocontrol. Compared with traditional long-term breeding efforts of incorporating disease resistance with other desirable traits, rootstock breeding can be more effectively performed as the focus may be mainly on root characteristics including resistance to soilborne diseases. Grafting also allows for better utilization of germplasm resources as rootstock development may make it easier to directly employ related or wild species for deploying new traits as compared to a traditional breeding program. For example, many commercial rootstocks are interspecific hybrids using a wild species as a parent. Hence, grafting offers broader opportunities for optimizing breeding outcomes by encouraging complementary programs of scion and rootstock cultivar development.

With the increase of organic production and other alternative farming systems requiring more restricted use of synthetic pesticides, and in the scenarios of growing heirloom or specialty cultivars lacking effective genetic disease resistance, grafting has become an even more useful tool to manage soilborne disease issues (Fig. 4). The soilborne fungal, oomycete, bacterial, or viral diseases that may be managed effectively by grafting to prevent or minimize fruit yield loss include but are not limited to (as rootstock development continues to advance):

Fungal and oomycete diseases:

Fusarium wilt (caused by *Fusarium oxysporum*) in tomato, pepper, eggplant, cucumber, watermelon, and melon

Fusarium crown and root rot (caused by *Fusarium oxysporum*; *Fusarium solani*) in tomato, pepper, watermelon, and cucumber (Fusarium root and stem rot)

Verticillium wilt (caused by *Verticillium dahliae*) in eggplant, tomato, watermelon, melon, and cucumber

Southern blight (caused by *Sclerotium rolfsii*) in tomato

Phytophthora blight (caused by *Phytophthora capsici*) in tomato and pepper

Monosporascus sudden wilt (caused by *Monosporascus cannonballus*) in melon and watermelon

Corky root (caused by *Pyrenochaeta lycopersici*) in tomato and eggplant

Black root rot (caused by *Phomopsis sclerotioides*) in cucumber

Gummy stem blight (caused by *Didymella bryoniae*) in melon (although not a soilborne disease, it occurs at the lower crown of the plant and may be managed by using resistant rootstocks)

Bacterial diseases:

Bacterial wilt (caused by *Ralstonia solanacearum*) in tomato, eggplant, and pepper

Nematodes:

Root-knot nematodes (*Meloidogyne* spp.) in tomato, eggplant, pepper, melon, watermelon, and cucumber

Figure 3. Large-scale production of grafted watermelon transplants in commercial nurseries in Spain (left) and China (center), and grafted tomato transplants in the U.S (right) *(Photos by Xin Zhao and Carol Miles).*

Viral diseases:

Melon necrotic spot virus in watermelon and melon

Most commercially available rootstocks do not have a complete resistance package. For instance, the interspecific hybrid squash rootstocks are highly resistant to Fusarium wilt but often lack resistance to root-knot nematodes. The rootstock should be selected to address the primary disease problem identified in the production system. Moreover, rootstock resistance to specific pathogen races should be considered; that is, a rootstock may have resistance to one race within a specific disease but not another race. For example, the interspecific tomato hybrid rootstock 'Maxifort' has high resistance to Fusarium races 1 and 2 but not race 3, while another interspecific tomato hybrid rootstock 'Multifort' possesses high resistance to all three races.

Although foliar disease resistance is largely determined by the scion cultivar and grafting has rather limited use in foliar disease management, tolerance of grafted plants to certain foliar diseases might be improved by using selected rootstocks, an area that deserves more research. For example, 'German Johnson' heirloom tomato grafted onto 'GRA 66' tomato rootstock was reported to show lower incidence of tomato spotted wilt virus compared with non-grafted 'German Johnson' (Rivard and Louws, 2008). In general, the overall health of plants may be promoted as plant vigor and growth increases with the use of selected rootstocks.

Grafting as an innovative method for overcoming abiotic stress and improving plant growth, fruit yield and quality

Even under low or no disease pressure, plant growth can be considerably improved especially when vigorous rootstocks are used and water and nutrient uptake becomes more efficient. Increased leaf photosynthetic rate and nitrogen assimilation and endogenous hormonal modification have been observed in grafted plants, and enhancement of plant performance is especially evident when plants are exposed to suboptimal growing conditions (e.g., low and high temperatures) during the production season (Aloni et al., 2010; Martínez-Ballesta et al., 2010).

Desirable root characteristics for nutrient and water uptake can be accomplished through rootstock selection and development. As a result, fruit yield (fruit size and/or fruit number) can be increased and harvest period expanded. For example, the double leader system is commonly used in hydroponic tomato systems to reduce number of transplants while increasing yields by taking advantage of growth vigor

Figure 4. Non-grafted 'Black Cherry' tomato (front) versus 'Black Cherry' grafted onto 'Multifort' rootstock (back) in an organically-managed high tunnel. The plant decline of non-grafted 'Black Cherry' was caused by Fusarium wilt *(Photo by Xin Zhao).*

promotion by grafting with interspecific hybrid tomato rootstocks (Fig. 5). Rootstocks with excellent tolerance to abiotic stresses such as low temperature, soil salinity, drought, and flooding, are also available to growers for early production and off-season cultivation as well as dealing with environmental constraints. This may add particular value to protected culture with continuous cropping systems that have limited rotation. Reduction in fertilizer and irrigation water use as well as the number of plants needed may be possible. On the other hand, plant vegetative growth and reproduction (fruit set) need to be well balanced through crop management practices (e.g., timing of nutrient application) when vigorous rootstocks are used.

Early flowering and fruit set may be achieved by grafting with certain rootstocks, and some fruit quality attributes may be enhanced, such as fruit size (although increased fruit size might be undesirable sometimes), firmness, and certain nutritional values (e.g., lycopene content),depending on the rootstock-scion combination (Aloni et al., 2010; Lee et al., 2010; Rouphael et al., 2010). However, possible grafting incompatibility might occur occasionally (assuming the decline of plants is not caused by poor quality of grafting and healing), and certain rootstock-scion combinations may also lead to delayed fruit set and ripening and reduced fruit quality such as soluble solids content (Guan et al., 2015). Consumer-perceived sensory properties such as fruit texture, sweetness, and flavor may also be negatively impacted, especially when rootstock and scion cultivars are more distant in their genetic makeup. Rootstock effects and rootstock-scion interactions will need to be examined to avoid negative influence of grafting on overall crop performance.

Advancing rootstock development and optimizing grafted vegetable production systems

While a "super" rootstock may not exist to address every production issue encountered, rootstock selection and breeding will continue to enhance multifaceted benefits of grafting in vegetable production. As new research tools become more readily available to better understand the basis for rootstock-scion "cross talk" at physiological, biochemical, and molecular levels, grafting technology is expected to enter a new era in advancing sustainability of vegetable production. Continued technology improvement of grafting (e.g., automation, suppression of rootstock regrowth) that produces high quality grafted seedlings with increased cost effectiveness will greatly facilitate economical production of grafted vegetables. Meanwhile, the increasing adoption of grafted transplants requires more in-depth research and technology transfer targeting optimization of management practices (e.g., fertilization and irrigation) of grafted vegetable plants in various production systems in order to realize the optimal gains of grafting.

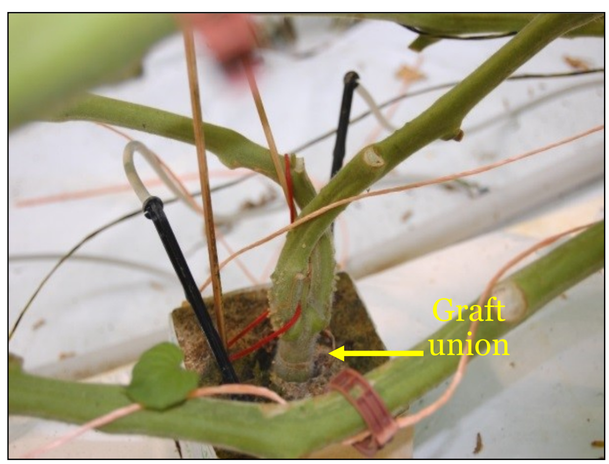

Figure 5. Hydroponic production of grafted tomato plants using a double-leader plant training system. *(Photo by Xin Zhao)*.

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