Chapter 2
Corylus

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2.1 Introduction

The *Corylus* L. genus contains a wide diversity of deciduous shrub and tree species that are important components of many temperate forests across the Northern Hemisphere, all bearing edible nuts. Its most widely known and well-studied member, the European hazelnut (*Corylus avellana* L.), is also an economically valuable commercial tree nut crop, ranking fifth in world production behind cashews (*Anacardium occidentale* L.), almonds [*Prunus dulcis* (Miller) D.A. Webb], walnuts (*Juglans regia* L.), and chestnuts (*Castanea* spp.) (FAOSTAT 2010). The top hazelnut producing country in the world is Turkey, which typically produces more than 70% of the world's crop, which was 1,052,001 tons in 2008. Turkey is followed by Italy, which produces around 15–20% of the total, and the US, which produces <5%. Other countries producing significant crops include Azerbaijan, Spain, Georgia, Iran, France, and China (FAOSTAT 2010). Commercial production is limited to regions with climates moderated by large bodies of water that have cool summers and mild winters, such as the slopes on the Black Sea of northern Turkey or the Willamette Valley of Oregon, where 99% of the US crop is produced. The demand for hazelnuts worldwide is predominated by a desire for round, high-quality, well-blanching kernels for use in chocolates and other confectionaries, baked goods, spreads, and other products. Only 10% or less of the world's crop is sold as in-shell nuts. Superior kernels of the Italian cultivars "Tonda Gentile de Langhe", "Tonda di Giffoni", and "Tonda Romana" set quality standards of comparison for the industry.

Hazelnut has a long history of utilization and production by man, likely predating the Roman era (Rosengarten 1984; Boccacci and Botta 2009). Despite this long history, hazelnut breeding is in its infancy compared to most other domesticated crops. Until only recently, world production has been based entirely on traditional selections made from local populations, whose exact origins have been largely lost with antiquity. Public breeding programs were initiated in Italy and the US in the 1960s, Spain and France in the 1970s, and Turkey in the 1980s (Thompson et al. 1996), but the *Corylus* genus as a whole remains essentially untouched by plant breeders. Outside of the US, traditional cultivars and local selections still represent a majority of the hazelnuts being established in production orchards today (Bozoğlu 2005; Tombesi 2005; Tous 2005; Sarraquigne 2005). Nevertheless, over the past several decades much has been learned about hazelnut genetics, biology, and production, and very effective traditional and molecular genetic improvement techniques have been developed (Mehlenbacher 1994; Thompson et al. 1996; Chen et al. 2005; Molnar et al. 2005; Mehlenbacher et al. 2006; Gökirmak et al. 2009). While most work has been centered on cultivated forms of *C. avellana*, the interspecific hybridization potential and genetic diversity of the genus is high, and substantial opportunities exist to utilize wild species in genetic improvement and research efforts (Mehlenbacher 1994; Erdogan and Mehlenbacher 2000a, 2001). In this chapter, the history, current status, and breeding potential of wild *Corylus* are discussed, prioritizing the need to conserve and better study underutilized wild species. Few surveys of wild *Corylus* have been made in recent

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years, and overdevelopment in many regions has increased the possibility that some species are experiencing unchecked genetic erosion. One species, *C. chinensis* Franch., is even considered endangered by the International Union for Conservation of Nature and Natural Resources (Sun 1998).

2.2 Botany of *Corylus*

The *Corylus* genus is widely distributed across temperate regions of the Northern Hemisphere, with species found in Japan, Korea, and China, through Tibet, India, northern Iran, Turkey, the Caucuses, Europe, and in North America, with none endemic to the Southern Hemisphere (Kasapligil 1972; Thompson et al. 1996). Most taxonomists place *Corylus* L. in the subfamily Coryloideae of the family Betulaceae, order Fagales (Chen et al. 1999; Yoo and Wen 2002). *Corylus* comprises anywhere from 9 to 25 species, depending on the authority, with current revisions based on morphological, molecular, and hybridization studies suggesting around ten polymorphic species assigned to four subsections (Thompson et al. 1996; Erdogan 1999; Erdogan and Mehlenbacher 2000a, b). Subsection "*Corylus*" includes three species whose major similarities include leafy, overlapping involucres (husks) covering the nuts (*Corylus avellana*, *C. americana* Marshall, and *C. heterophylla* Fisch.); subsection "*Siphonochlamys*" includes three species with tubular, bristle-covered involucres (*C. cornuta* Marshall, *C. californica* Marshall, and *C. sieboldiana* Blume.); subsection "Columnaea" includes three species that grow as single trunk trees (*C. colurna* L., *C. chinensis*, and *C. jacqemontii* Decne.); and subsection "*Acanthochlamys*" includes only *C. ferox* Wall, which has a spiny chestnut-like (*Castanea* L.) involucre unlike any other species in the genus (Erdogan and Mehlenbacher 2000a, b; Whitcher and Wen 2001). The little-studied paperbark tree species *Corylus fargesii* (Franch.) C.K. Schneid. (likely syn. *C. papyraceae* Hickel) has yet to be officially placed in a subsection.

Species range in size from small, multi-stemmed bushes (1 m) to large trees (up to 40 m). All members are deciduous, with simple, alternate leaves and monoecious wind pollinated flowers that undergo anthesis before leaves develop in the spring. Plants are self-incompatible and diploid; most researchers agree the chromosome number across the genus is $2n = 2x = 22$ (Thompson et al. 1996). *Corylus avellana* – the European hazelnut of commerce and the most widely studied of the genus – is believed to have a relatively small genome (0.48 pg/1C nucleus, 413 Mbp) (Bennet and Smith 1991), with all other members of the genus unreported.

2.2.1 Subsection Corylus

Corylus avellana: European hazelnut. Plants are multi-stemmed shrubs 3–10 m tall, with a growth habit ranging from very erect to drooping. Ornamental forms also exist that have weeping or contorted branches. Plants spread by suckers, but the rate and number of suckers produced from the base of the plant varies considerably. Shoots are glandular pubescent and vary in their thickness and branching density. Leaves range from 5–10 cm in length and are elliptic to ovate to rounded in shape, slightly cordate at the base, and have doubly serrate margins. Nuts develop in clusters of 1–12, each separately enclosed in an involucre made up of two overlapping, leafy bracts that vary considerably across the species in terms of the length, constriction around the nut, indentation and serration at the apex, and thickness at the base. Nuts of cultivated forms, which may or may not be released from the involucre at maturity, are by far the largest of the genus, although they vary tremendously in size, shape (from oblate to long and tapered), shell thickness, and percent kernel (ratio of kernel to shell by weight). Commercial production is found near coastal areas of Europe, the Caucasus, Asia Minor, and the Pacific Northwest of the US where the climate is moderated by large bodies of water. However, the native range of *C. avellana* is quite extensive, spanning northward to nearly 68°N in Norway and 61°N in Finland, eastward through St. Petersburg to 58°N in the Ural Mountains of Russia, and southward to 32°N in Morocco, bounded in the west by the Atlantic Ocean. It typically grows as a common understory shrub and forest edge species in mixed deciduous forests. Most authorities now include the previously named species *Corylus maxima* Mill., *C. pontica* Koch., and *C. colchica* Alb. as members of *C. avellana*, exemplifying its very diverse and polymorphic nature (Mehlenbacher 1991a; Thompson et al. 1996; Erdogan and Mehlenbacher 2000a, b). *Corylus avellana* was one of the first species to colonize Europe after the last ice age, with pollen records and chloroplast DNA variation studies suggesting expansion from refugia in southwestern France into most of Europe, except for southern Italy and the Balkans, where expansion was from local populations (Palme and Vendramin 2002; Boccacci and Botta 2009). While it is not certain when the domestication of hazelnut began (Zohary and Hopf 2004), Boccacci and Botta (2009, 2010) suggest, based on genetic, historical, and archaeological data, that the species was independently domesticated in the Mediterranean (Spain and Italy), Turkey, and Iran. More than 400 cultivars have been described (Gürcan et al. 2010). Descriptions were derived from Smolyaninova (1936), Kasapligil (1972), Deacon (1974), Mehlenbacher (1991a), and Thompson et al. (1996).

Corylus americana: American hazelnut. Plants are small multi-stemmed shrubs, 1–3 m tall, that spread by abundant suckers. Shoots and leaf petioles are glandular pubescent. Leaves range from 5–16 cm in length and are generally broadly ovate to round in shape with the base rounded or slightly cordate. The leaf apex is acuminate with serrate to doubly serrate leaf margins. Nuts develop in clusters of 2–8 with each nut enclosed in an involucre made up of two overlapping, enlarged, glandular-pubescent leafy bracts that are typically two times the length of the nut, with deep, irregular indentations at the apex. Nuts, which are retained in the involucre at maturity, are round to round-compressed in shape and 1.0–1.5 cm in diameter. Nuts are generally smaller and thicker-shelled then those of *C. avellana* but are similar in flavor and quality with variability observed in productivity, size, and other attributes across populations and individual plants. The species is native to a wide part of eastern North America from Saskatchewan and Maine in the northeast to Minnesota and southern Manitoba in the northwest, all the way south to northern Florida and westward to eastern Oklahoma. Plants grow as a forest edge species and along roadsides, fence rows, ravines, and streams, as well as in waste places and tall- and mid-grass prairie habitats. *Corylus americana* is considered an important wildlife and riparian species that is used as a component of shelterbelts and as an ornamental due to some plants expressing attractive bright red and/or pink fall color. Nuts of *C. americana* have been harvested and used locally from wild plants. Several cultivars producing larger-sized nuts have been selected in the past (see Sect. 2.5.2). Descriptions were derived from Weschcke (1954), Drumke (1964), Duke (1989), Mehlenbacher (1991a), Boufford (1997), and Gleason and Cronquist (1998).

Corylus heterophylla: Siberian hazel. Plants are multi-stemmed shrubs 1–3(7) m tall that spread by abundant suckers. Shoots and leaf petioles are glandular pubescent. Leaves range from 4–13 cm in length and are quite variable in shape from elliptic, elliptic-obovate, broadly ovate, or obovate to suborbicular. Some plants express two distinctly different leaf shapes with some having an acuminate apex and others an abruptly acuminate apex (truncate) and somewhat bi-lobed leaves with the apex not exceeding the lateral lobes. Leaves are cordate at the base with margins irregularly or doubly serrate. Nuts generally develop in clusters of 1–7 with each enclosed in an involucre made up of two slightly pubescent to densely pubescent glandular, bell-shaped leafy bracts that are normally slightly longer in length than the nut (although some can range from twice the nut length to being equal or shorter than the nut, while others are very short and not well developed). The husk displays deep, irregular indentations at the apex. Nuts, which may or may not be retained in the involucre at maturity, show great variability in size, shape, and shell thickness, but are generally round to ovoid and 0.7–1.5 cm in diameter. The species is native to a large area of Korea, Japan, China, eastern Mongolia, and the Russian Far East where it grows as an understory shrub in open forests, on forest edges, on deforested hills, in dry river valleys, and in vast thickets on mountain slopes. The nuts of *C. heterophylla* are regularly harvested from the wild and sold in domestic markets for food and oil, with some cultivars and interspecific hybrids selected and grown commercially in China and Korea. Two botanical varieties are recognized that have a more southerly distribution in China, which are considered separate species by some authorities. *Corylus heterophylla* var. *sutchuensis* (syn. *C. kweichowensis* Hu) grows 3–7 m tall and is distributed throughout the Shangxi, Sichang, Hubei, Hunan, Jiangxi, Zhejiang, and Guizhou provinces. *Corylus heterophylla* var. *yunnanesis* Franch., which can be found growing in high density in some areas, grows 1–3(5) m tall primarily in the Yunnan and

Sichuan provinces. Descriptions were derived from Smolyaninova (1936), Kasapligil (1972), Mehlenbacher (1991a), and eFloras (2009).

2.2.2 *Subsection* Siphonochlamys

Corylus cornuta: Beaked hazel. Plants are multi-stemmed shrubs 1–3 m tall, which spread by suckers and abundant below ground stolons. Shoots and petioles can be glabrous to pubescent, but non-glandular. Leaves range from 5–12 cm in length and are ovate to obovate or narrowly elliptic in shape, with an acuminate apex. They are slightly cordate at the base with margins irregularly doubly serrate. Nuts develop in clusters of 1–6, each tightly enclosed in a tube-like involucre (beak) that is constricted beyond the nut, measures 2–4 times its length, and is densely covered with bristly, irritating hairs. The nuts are retained in the involucre at maturity and are typically 1.0–1.5 cm in diameter, very thick shelled, and ovoid. The species is native to a broad section of North America, farther north and west than *C. americana,* although their ranges overlap significantly. It can be found in the northeast from Newfoundland and New Brunswick, Canada, through Maine to South Carolina and the mountains of Georgia in the southeast, and west to Alabama. In its northern range, it can be found west of New Brunswick, through southern Canada, across the upper Midwest US states, and north into Manitoba, Saskatchewan, and Alberta. It grows as an understory plant in open woodlands and clearings, as well as along moist to dry roadsides, at the edges of woods, and along streams, often at higher elevations. It can sometimes form very dense thickets, due to its stoloniferous habit, and has the ability to re-grow after forest fires. *Corylus cornuta* is not widely harvested or cultivated for its small, thick-shelled nuts, although several interspecific hybrids have been developed in attempts to access its extreme cold hardiness. Descriptions were derived from Buckman (1964), Drumke (1964), Mehlenbacher (1991a, 2003), Boufford (1997), and Gleason and Cronquist (1998).

Corylus californica (syn. *C. cornuta* var. *californica*). Plants are multi-stemmed shrubs 3–4 m tall that spread by suckers, lacking the stolons of *C. cornuta*. Young shoots and petioles are typically glandular pubescent, although glabrous in maturity. Leaves range from 4 to 7 cm in length and are rounded or obovate to broadly elliptic, with an obtuse to acute apex. Leaves are typically more cordate at the base than *C. cornuta*, with margins coarsely doubly serrate. Nuts develop in clusters of 2–4, with each tightly enclosed in a tube-like bristly involucre that is constricted beyond the nut and is generally two times its length or shorter. The nuts are usually larger than those of *C. cornuta* and are retained in the involucre at maturity. The species is native to western North America, from southern British Columbia southward through western Washington, Oregon, and central California. Plants are generally found along streams, on damp rocky slopes, and in cool canyons in the coastal mountain ranges. *Corylus californica* is not widely harvested for its nuts. Descriptions were derived from Drumke (1964), Mehlenbacher (1991a), and Boufford (1997).

Corylus sieboldiana (syn. *C. mandshurica* Maxim.). Plants are multi-stemmed shrubs, 2–6 m tall that spread by suckers. Young shoots and petioles are glandular pubescent. Leaves range from 5–12 cm in length and are round, broadly ovate, oblong, or oblong-obovate, with a mucronate-acuminate or caudate apex and cordate base. Leaf margins are dentate to irregularly and coarsely serrate. Nuts develop in clusters of 1–9 with each tightly enclosed in a tube-like bristly involucre that is constricted beyond the nut and is generally two times its length or longer. Nuts are typically small, thick-shelled, ovoid-globose, and pointed, with some having thin shells up to 1.5 cm in diameter. They are retained in the involucre at maturity. The species is native to Korea, Japan, northern China, and the Russian Far East (Primorsky and Khabarovsky regions), where it significantly overlaps the range of *C. heterophylla* but is much less abundant. It occurs in forest areas with moist, fertile soil high in organic matter. Nuts of *C. sieboldiana* are harvested from the wild, although harvesting is complicated by the bristly involucres. Descriptions were derived from Smolyaninova (1936), Kudasheva (1965), Mehlenbacher (1991a), and eFloras (2009).

2.2.3 *Subsection* Colurnaea

Corylus colurna: Turkish tree hazel. Plants are large single trunk, pyramidal trees, 20–40 m tall, with trunk diameters ranging from 30–60(120) cm. Young shoots are glandular pubescent, with distinctive corky and furrowed bark that is light-gray to gray in color. Petioles are slightly pubescent glandular although sometimes glabrous. Leaves range from 7–18 cm in length and are round, oval, ovate, obovate, wide-elliptical, to slightly lobed in shape with an acute apex and a cordate to deeply cordate base. Leaf margins are dentate to doubly serrate. Nuts develop in clusters of 2–10 with each enclosed in a fleshy, glandular-pubescent involucre that is 2–3 times longer than the nut, open at the apex, and deeply dissected almost to its base into numerous long-acuminate lobes. Nuts are ovoid-globose to nearly round to flat-compressed, sometimes extended-elliptical or angular and 1.0–1.5 cm in diameter, with thick shells that are connected strongly to the involucre at maturity, although selections have been described that release readily. The species is native to the Balkan Peninsula, Turkey, the Caucuses, and northern Iran, growing as scattered trees in deciduous and mixed coniferous forests. In the Caucuses, it can be found 840–1,750 m above sea level in shady, moist deciduous forests with soils high in organic matter. Nuts are harvested from the wild and used and sold locally. However, the species has been more widely used as a source of high quality timber for construction of buildings, boats, and furniture. It is grown as a low maintenance shade tree in Europe and the US and has also been used as a non-suckering rootstock for *C. avellana* (with limited use today) for nut production and for ornamental *Corylus*, such as the contorted form *C. avellana* "Harry Lauder's Walking Stick" and the weeping form *C. avellana* "Pendula". Descriptions were derived from Smolyaninova (1936), Kudasheva (1965), Kasapligil (1972), Duke (1989), and Mehlenbacher (1991a, 2003).

Corylus jacquemontii: Indian tree hazel. Plants are single trunk trees 12–15 m tall. Bark is thinner and less corky than *C. colurna*. Leaves range from 15–24 cm in length and are obovate in shape, with the base shallowly lobed and margins sharply serrate. Nuts develop in clusters of 1–5 in involucres up to three times the length of the nut, similar in appearance to *C. colurna* but less fleshy with non-glandular pubescence. The small (up to 1.5 cm), thick-shelled nuts are generally more easy to remove from the involucre than *C. colurna*. The species is distributed across Northeast Afghanistan, northern India, northern Pakistan, and western Nepal at 1,900–3,000 m above sea level. Nuts are harvested from the wild and sold in local markets. Descriptions were derived from Mehlenbacher (1991a, 2003), Thompson et al. (1996), and Farris (2000).

Corylus chinensis: Chinese tree hazel. Plants are large, single-trunk trees, 20–40 m tall, with trunk diameters up to 2 m. Young shoots and petioles are sparsely villous, stipitate glandular to glabrescent. Bark is considerably thinner and smoother than *C. colurna*. Leaves range from 8–18 cm in length and are ovate, ovate-elliptic, or obovate-elliptic in shape, with an obliquely cordate base and mucronate or shortly caudate apex. Leaf margins are irregularly and doubly serrate. Nuts develop in clusters of 2–12, each in a fleshy, tube-like pubescent to glabrous involucre longer than the nut and tightly constricted after the nut with a forked or toothed apex. Nuts are ovoid-globose and 1.0–1.5 cm in diameter with thick shells that are strongly attached to the involucre at maturity. The species is distributed across southern China in parts of the Shangxi, Sichuan, Hubei, Hunan, Yunnan, and Guizhou provinces where it is found as scattered trees on moist, forested mountain slopes. Its timber has been used in China for furniture and paneling. The species is now considered threatened due to its scarcity (Sun 1998). Descriptions were derived from Duke (1989), Mehlenbacher (1991a), and eFloras 2009.

Corylus fargesii: Paperbark tree hazel. Plants are single-trunk trees up to 25 m tall. Young shoots and petioles are pubescent. The peeling bark of older stems and the trunk is similar to that of river birch (*Betula nigra* L.), which is a major distinguishing characteristic separating the species from *C. chinensis*. Leaves range from 6–9 cm in length and are oblong-lanceolate, obovate-oblong, or lanceolate in shape, with the base cordate or sub-rounded and the apex acuminate. Leaf margins are coarsely and irregularly doubly serrate. Nuts develop in clusters of 2–4 each enclosed in a tubular involucre that is tightly constricted after the nut and measuring 2.0–5.0 cm long, with its apex divided into triangular-lanceolate lobes. Nuts are ovoid-globose and 1.0–1.5 cm in diameter. The species is distributed throughout mountain valleys of the Henan, Sichuan, Hubei, Shangxi, Gangsu, and Guizhou provinces of China. Descriptions were derived from Aiello and Dillard (2007), Farris (2000), and eFloras (2009). *Corylus fargesii* has not been officially placed in subsection Columnaea due to poor representation in taxonomic studies. However, morphological examination of recent introductions in the US suggests its likely inclusion. Also, *C. fargesii* may be a synonym for *C. papyraceae* Hickel; further investigation is needed to clarify its taxonomic position.

2.2.4 *Subsection* Acanthochlamys

Corylus ferox: Tibetan hazel and Himalayan tree hazel. Plants are single-trunk trees 6–9 (20) m tall. Young shoots are pubescent, sometimes stipitate glandular or glabrescent. Petioles are densely pilose when young, glabrescent later. Leaves are 5–15 cm long and are ovate-oblong, obovate-oblong, obovate, or elliptic in shape, with the base obliquely rounded or subcordate and the apex long acuminate to caudate-acuminate. Leaf margins are sharply and doubly mucronate serrate. Nuts develop in clusters of 3–6 in spiny, cup-shaped involucres unlike any of the other *Corylus* species. The clusters are very similar to spiny chestnut (*Castanea* L.) burrs. Nuts are ovoid-globose to slightly compressed and 1.0–1.5 cm in diameter. The species is native to forested mountain slopes 1,700–3,800 m above sea level in the eastern Himalayan Mountains from Bhutan, Northeast India, northern Myanmar, and Nepal to parts of the Yunnan, Sichang, and Xizang provinces of China. The botanical variety, *C. ferox* var. *thibetica* (Batal.) Franch., is recognized to differ from *C. ferox* by having less spines (or pubescence) on the base of the involucre and lacking pubescence on vegetative buds and young shoots. It is found in the Gansu, Guizhou, Hubei, Ningxia, Shaanxi, Sichuan, Xizang, and Yunnan provinces of China in mixed forests at 1,500–3,600 m above sea level. Descriptions were derived from Kasapligil (1972), Mehlenbacher (1991a), Thompson et al. (1996), Farris (2000), and eFloras (2009).

2.3 Conservation of Wild *Corylus* Genetic Resources

Essentially no work has been done to investigate population structure, genetic diversity, and possible genetic erosion (loss of genetic resources) of wild *Corylus* species. Nearly all efforts have been focused on cultivated forms of *C. avellana* largely to better understand their origin, to fingerprint germplasm accessions, and to evaluate genetic diversity present in collections (Bassil et al. 2005a, b, 2009; Boccacci et al. 2006, 2008; Boccacci and Botta 2009, 2010; Gökirmak et al. 2009; Gürcan et al. 2010). The most recent survey of *Corylus* in North America was conducted by Drumke (1964), though extensive land development since this time limits the usefulness of this work. Sun (1998) reported that *C. chinensis* was becoming scarce in China, leading to its threatened status. It is possible that genetic resources of other *Corylus* species are in danger of being lost, especially in highly populated countries or regions that have undergone widespread deforestation.

2.3.1 *World Germplasm Collections*

In general, world *Corylus* germplasm collections consist primarily of cultivated forms of *C. avellana* and are located in regions where production occurs. Major collections include the US Department of Agriculture (USDA), Agriculture Research Service (ARS), National Clonal Germplasm Repository (NCGR) in Oregon, US, with a backup collection at Parlier, California (Hummer 2001; Bassil et al. 2009); the Hazelnut Research Institute in Giresun, Turkey; Institut de Recerca İ Technologia Agroalimentàries (IRTA) in Reus, Spain; Institut National de la Recherche Agronomique (INRA) in Ponte-de-la-Maye, France; the University of Torino and the Institute Sperimentale per Frutticoltura in Italy; the (VIR) Breeding Station, Maykop, and the Russian Academy of Agricultural Sciences Institute of Floriculture and Subtropical Cultures, Sochi, Russia; and the Nikita Botanical Gardens in Yalta, Ukraine. These and a number of smaller collections are listed in Mehlenbacher (1991a), Koksal (2000), and Bacchetta et al. (2009). Throughout nearly all of these collections, wild *Corylus* species are very poorly represented, including uncultivated forms of *C. avellana* from across its native range. In recent years, the NCGR and Oregon State University have increased efforts to collect cultivated and wild accession of *Corylus*, and their collections now total more than 700 accessions between them representing all major *Corylus* species (Gürcan et al. 2010); however, a number of species are still lacking, especially when considering their wide

Table 2.1 Species accessions held at the US Dept of Agriculture, Agricultural Research Service, National Clonal Germplasm Repository in Corvallis, Oregon as of July 2010 (NCGR 2010). Subspecies and botanical varieties are included under the species headings

Species	Number of accessions	Countries of origin
Corylus americana	45	2
Corylus avellana	464	32
Corylus californica	49	1
Corylus chinensis	12	4
Corylus colurna	21	12
Corylus cornuta	19	2
Corylus fargesii	8	3
Corylus ferox	5	2
Corylus heterophylla	63	5
Corylus jacquemontii	6	4
Corylus sieboldiana	42	6

geographic range. Continued collection and evaluation efforts are still needed (Table 2.1).

In addition to specifically designated *Corylus* collections, many botanical gardens and arboreta around the world hold specimens of the genus. These specimens represent a valuable, yet largely untapped resource. Unfortunately, some trees in these settings appear to be mislabeled as to species or cultivar, and diversity across institutions may be limited due to direct sharing of germplasm and/or collaborative collection expeditions. Efforts are needed to identify, better characterize, and catalog *Corylus* plants existing in these settings to make them available for conservation, research, and breeding efforts. In the US, small but diverse collections can be found at the Morris Arboretum in Pennsylvania, the Brooklyn Botanical Garden in New York, the Dawes and Holden Arboreta in Ohio, the Arnold Arboretum in Massachusetts, the Morton Arboretum in Illinois, and likely others, both public and private.

2.3.2 Germplasm Preservation

Because *Corylus* seeds cannot be stored much longer than one year without losing viability, germplasm preservation is based on tree accessions grown in collection orchards. The expense of maintaining these orchards can be prohibitive, as exemplified by the land needed to grow trees of *C. colurna* and *C. chinensis*, which can reach well over 20 m tall. While a useful means to capture and preserve the genetic diversity of wild species is as trees derived from seeds of local origins, the outcrossing, highly heterozygous nature of *Corylus* requires selected genotypes (cultivars) be propagated by asexual methods to retain their genetic identity. Clonal propagation adds to the expense and challenge of obtaining, accurately maintaining, and distributing *Corylus* germplasm. This has been traditionally accomplished by layering, an effective yet inefficient practice, and to a lesser extent grafting. Grafting presents problems due to the suckering growth habit of the rootstocks typically used, excluding *C. colurna*, which has been used but is not widely available, partly due to its slow seed germination and poor ability to be transplanted in a nursery setting (compared to *C. avellana*). This problem is especially acute in germplasm collection settings where rootstock shoots can be confused with the original scion accession. Also, grafted plants do not have the capability to re-grow after mechanical injury and disease, like those on their own roots.

A micropropagation system for hazelnuts was recently developed that is effective for *C. avellana*, as well as interspecific hybrids of *C. avellana* with *C. colurna*, *C. americana,* and *C. heterophylla* (Yu and Reed 1995; Nas and Read 2004; Bacchetta et al. 2008; Gao et al. 2008). Micropropagation allows for very efficient clonal propagation and it is currently being used by commercial nurseries in the US. Since plants are on their own roots, they provide the same benefits as layered plants, but through a much more efficient propagation system. Micropropagation also provides a means for space-efficient in vitro preservation of germplasm. Currently, 70 accessions are backed up at the NCGR in the form of tissue culture plantlets, consisting mostly of economically important

C. avellana cultivars and *C. avellana* selections from the wild, with only a few other *Corylus* species available at present (Joseph Postman, personal communication). The aseptic process of tissue culture can also provide essentially disease- and virus-free plant material, which can aid in meeting quarantine regulations to facilitate sharing of genetic resources and improved cultivars.

For long-term germplasm preservation, a method to store hazelnut embryonic axes in liquid nitrogen was developed. Excised, dehydrated embryos of hazelnut seeds previously treated to a period of moist-chilling (stratification) survived freezing in liquid nitrogen to be thawed and grown successfully in tissue culture (Normah et al. 1994; Reed et al. 1994). Based on this work, embryonic axes of seeds from *C. americana*, *C. colurna*, *C. heterophylla*, and *C. sieboldiana* were cryo-preserved in liquid nitrogen and are stored at the National Seed Storage Laboratory in Fort Collins, Colorado (Reed and Hummer 2001). Cryopreservation of *Corylus* pollen is also possible (Craddock 1987), and pollen of 53 *C. avellana* cultivars has been preserved in liquid nitrogen for long-term storage at the NCGR. A clonal cryo-preservation technique is still needed, however. Research is underway at the NCGR to develop a method to preserve dormant vegetative buds. A major challenge to developing the clonal cryopreservation of hazelnuts has been grafting the buds, once thawed, to successfully regenerate new plants (Joseph Postman, personal communication, 2009).

2.4 Genetic Studies and Genomic Resources of Wild *Corylus*

Similar to the germplasm collection efforts discussed in the previous section, nearly all *Corylus* research – including genetic studies and genomic resources – has been focused on *C. avellana*. These advances have increased breeding efficiency and contributed to knowledge of pollen-stigma incompatibility (Mehlenbacher 1997), as well as helping to clarify the genetic control of many traits that should prove applicable to future studies and improvement efforts utilizing wild *Corylus* and interspecific hybrids. The inheritance of qualitative traits characterized for *C. avellana* include red leaf color (Thompson 1985), chlorophyll deficiency (Mehlenbacher and Thompson 1991), cut-leaf habit (Mehlenbacher and Smith 1995), pollen color (Mehlenbacher and Smith 2002), style color (Mehlenbacher and Thompson 2004), contorted growth habit (Smith and Mehlenbacher 1996), non-dormancy (Thompson et al. 1985), self-compatibility (Mehlenbacher and Smith 2001, 2006), and resistance to eastern filbert blight (EFB), a destructive fungal disease caused by *Anisogramma anomala* Peck E. Müller that has severely limited hazelnut cultivation in eastern North America (Fuller 1908; Thompson et al. 1996), from *C. avellana* "Gasaway", "Zimmerman", "Ratoli", OSU 408.040, and OSU 759.010 (Mehlenbacher et al. 1991; Chen et al. 2005; Lunde et al. 2006; Sathuvalli 2007). The inheritance of numerous quantitative traits has also been examined, which should prove applicable in interspecific improvement efforts. These include EFB resistance (Coyne et al. 1998, 2000), bud mite resistance (Thompson 1977a), pellicle removal (Mehlenbacher and Smith 1988), nut and kernel defects (Mehlenbacher et al. 1993), and other morphological and developmental characteristics related to commercial nut production (Thompson 1977b; Yao and Mehlenbacher 2000).

Recent studies have used sequence data from the nuclear ribosomal DNA internal transcribed spacer (ITS) region, 5S rRNA, chloroplast *mat*K, and ribulose-bisphosphate carboxylase (*rbc*L) gene regions to discern phylogenic relationships in *Corylus* and within the Betulaceae family (Chen et al. 1999; Erdogan and Mehlenbacher 2000b; Forest and Bruneau 2000; Whitcher and Wen 2001). Sequences of these genes for most wild species are accessioned and available through GenBank (2010); however, the numbers of genotypes from which the sequence data have been derived are limited. While these conserved gene regions are useful to distinguish between species, they tend to provide low intraspecific resolution, which limits their use in population studies. Fortunately, microsatellite or simple sequence repeat (SSR) markers that provide a higher level of resolution have recently been developed and used to successfully study genetic diversity and relationships of cultivated *C. avellana* (Bassil et al. 2005a, b; Boccacci et al. 2006; Gökirmak et al. 2009), with many markers (about 200) placed on a saturated genetic linkage map (Mehlenbacher et al. 2006; Mehlenbacher 2009; Gürcan et al. 2010). Bassil et al. (2005b) showed some SSR markers developed for *C. avellana* provide cross amplification in *C. americana*, *C. heterophylla*, *C. chinensis*, *C. colurna*, and *C. californica*, although no wild *Corylus* genetic diversity studies have yet to be completed. Work, however, is underway at Oregon State University, in Corvallis, Oregon, to assess the genetic diversity of *C. americana* accessions held in their collection, the NCGR, and other locations in the US, using SSR markers (Shawn Mehlenbacher, personal communication). Hopefully the development of SSR markers will open doors for similar studies with additional *Corylus* species in the near future.

Marker-assisted selection (MAS) techniques have been developed to identify seedlings carrying the "Gasaway" single dominant gene for EFB resistance, as well as resistance genes from "Ratoli", OSU 408.040, and OSU 759.010, using random amplified polymorphic DNA (RAPD), amplified fragment length polymorphisms (AFLP), and other PCR-based DNA marker systems (Mehlenbacher et al. 2004; Chen et al. 2005; Sathuvalli et al. 2009). These tools greatly increase the efficiency of breeding for resistance and should be useful for advanced-generation interspecific hybrids derived from these breeding lines. In addition, MAS has been developed for identifying desired sporophytic self-incompatibly *S*-allele genotypes, although to date RAPD markers have only been identified linked to the *S1* and *S2* alleles (Pomper et al. 1998). With further development, this system will allow breeders to identify *S*-alleles at a much earlier stage, saving valuable time and resources that are currently expended on growing seedlings until they flower to test incompatibility reactions against known tester genotypes using florescence microscopy (Mehlenbacher 1997). Very recent work involves the development of a bacterial artificial chromosome (BAC) library for the new *C. avellana* release "Jefferson" (OSU 703.007), which is intended to be used for map-based cloning of the "Gasaway" EFB-resistance gene and the sporophytic incompatibility locus (Mehlenbacher 2009; Sathuvalli and Mehlenbacher 2009). In addition, efforts are in place to begin sequencing of the genome of *C. avellana* (S. Mehlenbacher, personal communication, 2010). Once complete, these critical advances will provide great opportunities to improve the understanding, utilization, and conservation of *Corylus* genetic resources.

2.5 Role of Wild *Corylus* in Crop Improvement

Plants of *Corylus* (despite its self-incompatibility system) are typically very amenable to breeding compared to nearly all of the other temperate nut crops of world importance. Generation times are shorter (3–5 years to maturity), the plant size is smaller in stature, female flowers stay receptive to pollen for several weeks or longer, flowers are easy to isolate from foreign pollen, pollen is readily collected and stored for up to one year, and hand pollinations can yield large numbers of hybrid seeds (Thompson et al. 1996). All *Corylus* species produce edible nuts of relatively similar quality, although size, shell thickness, amount of fiber on the pellicle, and other characteristics may vary. Furthermore, the interspecific hybridization potential within *Corylus* is high, as discussed by Mehlenbacher (1991a), Thompson et al. (1996), and Erdogan and Mehlenbacher (2000a). In general, successful hybrids can be readily created between members of the same subsection (Corylus, Siphonochlamys, and Colurnaea), with crosses between the different subsections more limited, but in many cases, also possible. It should be noted that reciprocal differences have been observed in many crosses, and crosses with *C. avellana* have been generally more successful when the species was used as the staminate (pollen) parent. Interestingly, when *C. californica* was used as a pistillate parent, it was compatible with all other *Corylus* species tested, suggesting that it may have value as a bridge species (Erdogan and Mehlenbacher 2000a). Erdogan and Mehlenbacher (2001) also suggest that sporophytic incompatibility may exist in wild *Corylus* species, similar to that reported for *C. avellana*, where incompatibility is controlled by a single *S*-locus with multiple alleles (Thompson 1979; Mehlenbacher 1997), although many undetermined *S*-alleles and the presence of other barriers to hybridization appear to be involved. While further work is needed to clarify the incompatibility system in wild *Corylus*, many desirable and economically useful characteristics are present that can be accessed through interspecific hybridization in wild species, which are lacking in cultivated *C. avellana*. Traits of interest include non-suckering growth habits, tolerance of alkaline soils, extreme precocity, early maturing nuts, extreme cold hardiness, drought tolerance, attractive fall color and other ornamental attributes, rare incompatibility alleles, and novel sources of resistance to EFB. Most genetic improvement efforts will likely continue to be centered on cultivated forms of *C. avellana* due to its superior nut quality, yield, and other commercial production characteristics, with wild species used as donor parents to contribute desired traits by following some form of a modified backcross program. A number of examples are discussed later in this section where interspecific hybrids, sometimes difficult to create (as in *C. colurna* × *C. avellana*), are more easily backcrossed to either parental species, suggesting barriers to hybridization are reduced in advanced-generation hybrids.

Table 2.2 presents current breeding objectives and standards of *C. avellana* seedling evaluation in the OSU hazelnut breeding program, which is the largest and longest running hazelnut breeding program in the world (Mehlenbacher 2009). This table provides minimum selection criteria of seedlings that are necessary to develop improved cultivars to meet the demands of the international kernel market (Mehlenbacher 2003). Hybrid hazelnuts developed for production in new regions will not only require enhanced adaptation capabilities, including resistance to local pests and diseases – especially EFB if grown in North America – but they will also need to meet kernel quality standards to be competitive in the world market. Nearly all genetic studies of hazelnut have centered on cultivated *C. avellana*. As such, efforts are needed to characterize and better understand the inheritance of traits from wild species to enhance the efficiency of interspecific breeding efforts. It is especially important to recognize that the use of wild species in breeding may be accompanied by varying levels of undesirable traits, some which are unstudied and may be linked to characteristics of interest. Fortunately, a number of first-generation hybrids exist from early breeding efforts, as discussed below, which should prove useful in breeding more widely adapted cultivars. However, to maintain and enhance genetic diversity, breeders will also need to make additional first generation interspecific hybrids to widen the germplasm base and to better exploit the potential of *Corylus*. To be most effective, much more extensive collection of wild germplasm – and subsequent evaluation of these collections – must be made to further understand and best use existing genetic variability.

Table 2.3 presents desirable breeding attributes, potential limitations, and known interspecific compatibilities of the 11 most widely recognized *Corylus* species. Their history of use, if available, and a thorough description of their possible roles in genetic improvement are discussed below.

2.5.1 Corylus avellana

Due to its outcrossing, highly heterozygous nature, substantial genetic diversity can be found in the pool of existing *C. avellana* cultivars. This wide diversity,

Table 2.2 Objectives and standards of seedling selection in the Oregon State University hazelnut (*Corylus avellana*) breeding program, adapted from Mehlenbacher (2003). In addition to these requirements, all plants developed for North America should express a very high level of resistance to infection by *Anisogramma anomala*, which causes eastern filbert blight. For many locations, cold hardiness of plants, especially the male flowers (catkins), is also vital

Objective	Age at evaluation	Minimum standard (cultivar)	Ideal standard (cultivar)
Bud mite resistance	4	'Casina', 'Clark' (moderate resistance)	'Barcelona' (highly resistant)
Round nut shape	4–5	'Tonda Gentile delle Langhe'	'Willamette'
High percent kernel	4–5	'Tonda Romana' (48%)	Casina (56%)
Precocity	5	At least 35 nuts produced	–
Yield (total, consistency)	4–16	'Barcelona'	'Lewis'
Kernel blanching	5–8	'Barcelona'	'Negret'
Few nut and kernel defects	4–16	'Barcelona'	–
Early maturity	5–8	'Barcelona'	'Tonda Gentile delle Langhe'
Free-falling nuts at harvest	5–8	'Casina' (70% are free falling)	'Barcelona' (95% are free falling)

Table 2.3 Summary of positive breeding attributes, possible limitations, and hybridization potential of the eleven most widely recognized *Corylus* species. Compatibility is based on Erdogan and Mehlenbacher (2000a) and Thompson et al. (1996)

		C. avellana	*C. americana*	*C. heterophylla*	*C. cornuta*	*C. californica*	*C. sieboldiana*	*C. colurna*	*C. jacquemontii*	*C. chinensis*	*C. fargesii*	*C. ferox*
Positive attributes	Diversity of cultivated forms	••										
	Large nut and kernel size	••										
	Early maturing nuts	•			••	••						
	High yield potential/ productive selections	••	•	•								
	Cold hardiness	•	••	••	••		••	••				
	Drought tolerance		•	•	•		•	•				
	Heat tolerance	•	•	•								
	Small growth habit for high density planting		•	•	•							
	Stoloniferous habit[a]				•							
	Non-suckering tree form							•	•	•	•	
	Releases nuts from involucres	••		•								
	Precocious (produce nuts at young age)		•	••								
	Ornamental attributes[b]	•	•	•				•		•	•	
	Resistance to EFB	•	••	¤	•	•	¤	•	?	¤	¤	?
Possible limitations	Small, thick-shelled nuts		•	•	••	•	••	•	••	••	••	•
	Late maturing nuts		•				•			•		
	Cold sensitive	•				•				•	•	•
	Husk retains nut at maturity		••	•	•	•	•	•	•	••	••	•
	Involucres covered with irritating hairs				••	•	••					
	Suckering growth habit	•	••	••	••	••	••					
	Stoloniferous growth habit[a]				•							
	Susceptible to EFB	••						¤	?			?
	Not precocious							•	•	•	•	
	Limited germplasm			•			•	•	••	••	••	••
Compatibility (as female parent)	*C. avellana*	••	••	••			•	•	?		?	?
	C. americana	••	••	•		•			?		?	?
	C. heterophylla	•		••					?		?	?
	C. cornuta	¤		••	••	••	••		?		?	?
	C. californica	••	••	••	••	••	••	••	?	•	?	?
	C. sieboldiana	¤	••		••	••	••		?		?	?
	C. colurna	••		•		•		••	?	••	?	?

(*continued*)

Table 2.3 (continued)

	C. avellana	*C. americana*	*C. heterophylla*	*C. cornuta*	*C. californica*	*C. sieboldiana*	*C. colurna*	*C. jacquemontii*	*C. chinensis*	*C. fargesii*	*C. ferox*
C. jacquemontii	?	?	?	?	?	?	?	••	?	?	?
C. chinensis	••	••					••	?	••	?	?
C. fargesii	?	?	?	?	?	?	?	?	?	••	?
C. ferox	?	?	?	?	?	?	?	?	?	?	••

• Characteristic observed (cross is compatible)
•• Characteristic very prominent (high level of compatibility)
¤ Characteristic observed on rare occasion but more evaluation needed (compatibility reported but not regular)
? Unknown, has not been evaluated
[a]Stoloniferous growth habit is listed as both a positive attribute and a potential limitation, as it can be useful for soil reclamation and planting on marginal sites, but is not advantageous for commercial production
[b]Ornamental attributes vary between species. *C. avellana*: contorted and weeping stems, red/purple or yellow leaves, dissected leaves; *C. americana*: pink/red fall color, frilly involucres, small growth habit; *C. heterophylla*: lobed and truncated leaf habits; *C. fargesii:* attractive peeling bark

expressed as morphological, phenological, and DNA sequence variability, has been discussed by numerous authors, including more recently Mehlenbacher (1991a, b, 1997), Thompson et al. (1996), Erdogan (1999), Boccacci and Botta (2009, 2010), Boccacci et al. (2006, 2008), Biodiversity et al. (2008), Gökirmak et al. (2009), and Gürcan et al. (2010). World germplasm collections hold numerous cultivars, many of which are well characterized and, in recent years, have become more readily available for use in breeding and research efforts (Bacchetta et al. 2009; NCGR 2010). Access to rapid international mail services makes it possible to share pollen and scion wood to facilitate germplasm exchange and breeding efforts between and within many countries. In addition, efficient breeding techniques have been developed (Thompson et al. 1996) and many traits vital to improved nut quality and nut production, such as percent kernel, kernel weight and nuts per cluster, have been shown to be moderately to highly heritable, as discussed by Thompson (1977b), Mehlenbacher (1991a), Thompson et al. (1996), Mehlenbacher et al. (1993) and Yao and Mehlenbacher (2000). These facts, in combination with the paucity of modern breeding efforts and wide genetic diversity of *Corylus*, have set the stage for rapid gains in the genetic improvement of hazelnut, which is exemplified by several new EFB-resistant cultivars released from the Oregon State University breeding program. These improved cultivars, which are the result of systematic breeding efforts over the past 30 years, will save the US hazelnut industry considerable production costs due to their significantly reduced fungicide requirements and other disease management constraints (Julian et al. 2009a), and increased yields of high-quality kernels per hectare, compared to the traditional standard in Oregon, "Barcelona" (Mehlenbacher et al. 2007, 2008, 2009).

While cultivated forms of *C. avellana* typically express better nut quality and production characteristics than their wild counterparts, most are not reliably yielding outside of Mediterranean-like climates. Many lack cold hardiness, especially of staminate flowers, as well as other traits necessary for wide adaptation and consistent yields of nuts. Breeders will need to search for genetic resources outside of cultivated forms when intending to significantly expand the regions where hazelnuts can be produced commercially. Fortunately, cold-hardy, wild *C. avellana* exist that grow as far north as coastal Scandinavia, as well as in the Ural Mountains of Russia, the Carpathian Mountains of Poland, and other inland areas of Europe with continental climates periodically exposed to extreme temperatures. Through intraspecific hybridization, these cold-hardy wild forms represent a plausible means to substantially improve the climatic adaptability of cultivated hazelnuts. Select plants should provide a more rapid means to achieve this goal then by using other *Corylus* species. This is because, barring specific incompatibility alleles, wild *C. avellana* is fully compatible with the cultivated forms, which would allow for larger numbers of hybrid seed from controlled crosses, and the resulting progeny would be fully fertile, unlike some interspecific hybrids (Erdogan and Mehlenbacher 2000a). In addition, wild *C. avellana* exist that express traits amenable to commercial production that are not widely found in other *Corylus* species, such as short involucres that release the nuts on maturity, thin shells, high percent kernel, and upright growth habits. Other traits of *C. avellana* worthy of exploration include resistance to diseases and pests, such EFB and big bud mite (*Phytoptus avellanae* Nal. and *Cecidophyopsis vermiformis* Nal.) (Thompson et al. 1996; Lunde et al. 2000; Molnar et al. 2007; Chen et al. 2007; Sathuvalli et al. 2010). Unfortunately, wild *C. avellana* is poorly represented in world germplasm collections, especially from its most northern range. Collection and evaluation efforts remain necessary to access its full potential in breeding.

The first breeding work using wild *C. avellana* to develop cultivated hazelnuts for colder regions began in the early 1900s. The most notable was done in the Michurinsk and Moscow provinces of Russia, as discussed below, with minor efforts made in Ukraine (Slyusarchuk and Ryabokon 2001, 2005), Belarus (Volovich and Chripach 1998), and Estonia (Kask 1998, 2001). Commercial hazelnut production is currently limited to southern regions of the former Soviet Union near Sochi, Russia, the Caucasus Mountains along the Black Sea, and southern Crimea, Ukraine.

2.5.1.1 I.V. Michurin

In the early 1900s, under the direction of the famous Russian plant breeder I.V. Michurin, attempts at developing more cold-hardy hazelnuts were started at an independent genetics lab in the Tambov province of

Russia, which was then part of the Agricultural Academy of Science of the Soviet Union (the current name is the All Russian Scientific Research Institute of Genetics and Breeding of Fruit Species named after I.V. Michurin). Michurin and his colleagues I.S. Gorshkov and S.K. Chaplyaev hybridized southern cultivars with cold-hardy wild *C. avellana* from the Tambov region of Russia, with goals of developing plants that combined the high quality and large nut size of the southern cultivars with the cold hardiness of local hazelnuts (Pavlenko 1957). The southern cultivars “Adygeisky” and “Panakhesky”, which were widely grown in the Krasnodar region of Russia at the time, were used as pistillate parents for the first generation hybrids with the northern *C. avellana*. From these crosses, they planted a reported 200,000 hybrid seedlings for evaluation at the breeding station in Michurinsk (Denisova 1975). They assessed this very large population for cold hardiness, nut yield, and kernel quality, and selected only cold-hardy plants that produced nuts with more than 40% kernel by weight for further evaluation. Only 1% of this large population met these criteria and these plants were then used to create a second generation of progeny with breeding objectives to combine yield and cold hardiness with resistance to weevils (likely *Curculio nucum* L). The southern cultivars “Gigantsky Gallsky” and “Barcelona” were used as recurrent parents for this second generation of hybrids. Significant improvement was reported from this generation, as 20% of the progeny expressed desirable characteristics. From this work, Pavlenko (1957) described ten selections that were productive in regions where temperatures drop to −34°C. In the years that followed, a third generation of seedlings was grown, largely from open-pollinated seed collected from improved selections, with 25% of the resulting plants expressing improved nut characteristics (Denisova 1975). Breeders eventually selected 53 plants that expressed improved cold hardiness and very consistent annual yields. However, even in these advanced generations, it remained a challenge to obtain high yields. Denisova (1975) describes the top two selections from the Michurinsk program as very cold hardy, productive, and pest resistant: Selection 4–24, derived from the open-pollination of an unreported parent, has nuts that are 22 × 15 × 15 mm and 45% kernel, which is 53.2% oil by weight; Selection 5–10, also derived from the open-pollination of an unreported parent, has nuts that are 20 × 13 × 12 mm and 50% kernel, which is 63.2% oil by weight. While breeding work has been terminated, the Michurinsk Institute hazelnut collection currently holds more than 50 cold-hardy cultivars and forms (Director N.I. Savelev, personal communication, 3 July 2009). Breeding selections from the Michurinsk breeding efforts, although not widely available, represent valuable genetic resources inherently useful for continuing efforts to develop further improved cold-hardy cultivated hazelnuts.

2.5.1.2 A.S. Yablokov

A program similar to the one in Michurinsk was started in the 1930s by A.S Yablokov at the All Union Scientific Research Institute of Forestry and Mechanization in Moscow province (now called the All Russian Scientific Research Institute of Forestry and Mechanization). After unsuccessful attempts at growing seedlings of many southern cultivars in Moscow province to identify cold hardy individuals, in 1933–1935 a new approach was taken. Mother trees were selected from local wild *C. avellana* and were crossed with pollen collected from cultivars in Sochi (largely “Barcelona”, but also “Kudryavchik”, “Cherkesskii II”, “Yevgenia”, and “Brunsvik”). Reciprocal crosses were also made in Sochi on similar cultivars using pollen from select wild northern hazelnuts. The resulting seedlings were germinated at the agricultural experiment station in Moscow province and were field planted in 1938 and 1939 for evaluation. Open-pollinated seedlings of “Barcelona” from Sochi were planted for comparison. All of the “Barcelona” seedlings expressed poor growth and were killed by frost in their first years of life (Yablokov 1962; Kudasheva 1965). Around 50% of the hybrid progeny also perished due to the cold, although they persisted longer than the “Barcelona” seedlings. Of the remaining progeny, a small proportion continued to grow but was continually damaged by frost each year and produced little fruit, while the rest were winter hardy, vigorous, and productive. From these, several superior selections were identified as being exceptionally cold-hardy, producing staminate flowers tolerant of very cold test winters in Russia with improved nut size over the wild type. Other selections were found with nuts similar in size to southern cultivars, although their hardiness was not remarked upon.

Yablokov also collected open-pollinated seeds from select plants growing at the Michurinsk breeding station and grew them in Moscow province. From this plant material, promising hazelnuts were also selected. In 1948, several of the best hybrid plants were used in second-generation crosses, mostly with other selections from the Moscow institute. In addition, large populations were grown from seeds derived from open pollination of the best selections. From these populations, additional improved selections were identified, with a large focus on plants with red leaves (Kudasheva 1965).

2.5.1.3 R.F. Kudasheva

In 1954, R.F. Kudasheva continued Yablokov's breeding and evaluation work at the All Union Scientific Research Institute of Forestry and Mechanization. In addition to continuing evaluations of the breeding nurseries, in 1957 she made controlled crosses with additional southern cultivars growing in Azerbaijan with pollen from advanced hybrid selections from Moscow and wild Moscow plants. From 1957 to 1964, she created and evaluated more than 16,000 hybrids, with plant material grown and evaluated in Tambov, Moscow, and Krasnodar regions of Russia. Breeding efforts were largely discontinued in the late 1960s, but a number of notable cold-hardy cultivars were released, including "Tambovsky pozdniy", "Tambovsky rannii", "Moskovsky rubin", "Moskovsky rannii", and "Severnii 42", several of which were recommended for planting on the central chernozem region of the central (former) USSR (Pavlenko 1985). Today, a collection of plant material derived from this early work remains at the All Russian Scientific Research Institute of Forestry and Mechanization. It holds around 350 wild hazelnut selections from the Tambov region, as well as around 500 hybrid selections from the past breeding efforts. Of these, 150 have red leaves (Eugene Momonov, personal communication, 2003). A number of the Moscow selections are also held at the All Russian Scientific Research Institute of Genetics and Breeding of Fruit Species named after I.V. Michurin in Michurinsk (Director N.I. Savelev, personal communication, 3 July 2009). Around 50 selections were imported from the Moscow institute in 2003 and are under evaluation at Oregon State University and Rutgers University in New Jersey. A number of these Moscow plants were found to be EFB-resistant in Oregon (Sathuvalli et al. 2010). Select genotypes will be used in breeding and eventually preserved at the NCGR.

2.5.2 Corylus americana

The wild American hazelnut, *Corylus americana*, can be found growing across a wide range of climates and soils throughout much of eastern North America. Several *C. americana* selections have been identified and named that produce relatively large size nuts with good quality ("Rush", "Winkler", and "Littlepage"); however, most plants produce tiny nuts with thick shells that are of little commercial value. Wild hazelnuts were collected more widely in the past for home consumption and local sale, with few collected today. *Corylus americana* is the natural host of the fungus *Anisogramma anomala*, which causes EFB disease. While *C. americana* can vary in its response to the fungus, it is typically highly tolerant of the disease, with infected plants developing only tiny cankers, or none at all. Alternatively, the European hazelnut, *C. avellana*, is highly susceptible to this disease, which causes severe stem cankering, die back, and death of most plants within 4–10 years after exposure (Johnson and Pinkerton 2002). While the European hazelnut was likely brought to eastern North America as early as the first settlers from Europe (Rosengarten 1984), its production never became established there, largely due to EFB and compounded by the harsher climate of the northeastern US, compared to Europe (Fuller 1908; Thompson et al. 1996). Alternatively, European hazelnut production thrived in the Pacific Northwest for almost 100 years due its Mediterranean-like climate and lack of EFB in this region. Unfortunately, this situation changed in the late 1960s, with the introduction of EFB into southwest Washington (Davison and Davidson 1973). After first devastating most of the production orchards in Washington, EFB spread south and is now found throughout the entire Willamette Valley where its control measures (ample fungicide applications, pruning, etc.) add much expense to current production (Julian et al. 2009a).

Fortunately, the typically EFB-tolerant *Corylus americana* hybridizes readily with *C. avellana* (Erdogan and Mehlenbacher 2000a) and resistant progeny can be recovered from the cross, although transmission of resistance has not been well studied and appears to be controlled by multiple genes, as well as single dominant genes in some genotypes (Thompson et al. 1996; Molnar et al. 2009). It should also be noted that any hazelnut cultivar developed for North America should express a high level of tolerance or resistance to EFB in order to be economically and environmentally sustainable. A number of attempts have been made in the past to exploit *C. americana* to develop better-adapted, cultivated forms of hybrid hazelnuts, as discussed in more detail later in this section. While progress has been made over the past century to develop improved hybrids, inadequate funding, intermittent efforts, lack of knowledge about EFB, and poor access to diverse genetic resources has limited the achievements of these breeding efforts. However, the potential for *C. americana* in breeding remains very promising, especially in advanced generations backcrossed to superior forms of *C. avellana*.

Currently, germplasm collections of *C. americana* can be found at the NCGR and OSU, as well as the USDA National Resource Conservation Service Plant Materials Center in Elsberry, Missouri, with few accessions in other collections worldwide. Based on its extensive native range, existing collections do not fully represent the genetic diversity present in the species. Therefore, larger collection and evaluation efforts are needed to assess and utilize its full potential for breeding and the conservation of genetic resources. In addition to cold hardiness and resistance to EFB, selections made from its southern distribution may add heat tolerance or low-chill requirements needed to grow hazelnuts for production in more southern latitudes. Furthermore, select forms of *C. americana* and hybrids with *C. avellana* have shown high yield potential (Hammond 2006), and their smaller growth habit may be amenable for developing high-density plantings, which would provide earlier economic returns than more widely spaced orchards (Julian et al. 2009b). Small-statured plants also open up the possibility of mechanically harvesting crops directly from the bushes using modified versions of machines similar to those used for harvesting blueberries (*Vaccinium* spp.) or grapes (*Vitis* spp.). This method of harvesting would be opposed to collecting nuts from the orchard floor, as is now done in most commercial settings outside of Turkey, where hazelnuts remain harvested from the bushes by hand (Thompson et al. 1996). Mechanically harvesting the nuts directly from the bushes would reduce or eliminate the need for clean cultivation of the orchard floor, which would allow more sustainable planting on sloping land due to its reduced opportunity for soil erosion. This method of harvesting would also lessen the need for new cultivars to release their nuts cleanly from the involucre upon maturity – a trait lacking in most wild *Corylus* that is necessary to meet current mechanical harvest methods. *Corylus americana* also has value as an ornamental, as many selections express striking red and pink fall color, a trait not typically found in others of the genus. Also, their oversized, frilly involucres provide an additional ornamental attribute, especially when hybridized with purple-leaf *C. avellana*, as the purple color remains expressed in these tissues late into the summer even as the leaves typically fade to dark green.

2.5.2.1 J.F. Jones

After a thorough study of introduced cultivars, J.F. Jones of Lancaster, Pennsylvania believed there was little chance production of European hazelnuts could succeed in the US, outside of the Pacific coast. To remedy this situation, in 1917 he began attempts to hybridize cultivars of *C. avellana* with a locally selected wild hazelnut, *C. americana* “Rush”, which was well-adapted, high-yielding, and produced relatively large-sized nuts for the species (Reed 1936; Crane and Reed 1937). Jones’ apparent goal was to combine the cold hardiness of the native species with the larger nut size and thin shell of the European cultivars. He was unsuccessful in acquiring hybrid seed from his crosses for 2 years during which he used “Rush” solely as the staminate (pollen) parent. Finally, in 1919 he used “Rush” as the pistillate parent and subsequently developed the first reported interspecific hybrids of the two species. He used *C. avellana* “Barcelona”, “Cosford”, “Daviana”, “Italian Red”, and “Duchilly” as staminate parents and grew and evaluated many hybrid progeny. Unfortunately, he passed away in 1928 before final evaluations of his hybrids could be made. However, two plants that stood out early as being superior were released from his estate in the 1930s. They were named “Bixby” (“Rush” × “Italian Red”) and “Buchanan” (“Rush” × “Barcelona”). While neither proved to warrant commercial planting, they were described as being productive, cold-hardy, and suitable for home cultivation (Reed 1936; Crane and Reed 1937; ASHS Press 1997). While "Bixby" appears to be lost from cultivation, *C. americana* "Rush" and "Buchanan" are available from the NCGR.

2.5.2.2 C.A. Reed

The use of "Rush" as a parent in interspecific hybridizations was continued by C.A. Reed of the Bureau of Plant Industry, US Department of Agriculture in Beltsville, Maryland. From 1928 to 1932, Reed made hybrids with "Rush", using *C. avellana* staminate parents similar to Jones', as well as using "Hall's Giant", "Kentish Cob", "Red Aveline", and several others. He also made crosses, although to a much lesser extent, with *C. americana* "Winkler" from Iowa and "Littlepage" from Indiana, as well as intraspecific crosses between various *C. avellana* cultivars growing at the Bixby nursery in eastern Long Island, New York (Reed 1936; Crane and Reed 1937). From Reed's breeding effort, around 2,000 plants were provided for evaluation at the USDA experiment station in Maryland. Seedlings were also sent for evaluation to the New York State Agricultural Experiment Station in Geneva, New York. No additional hybrids were made by Reed; however, the resulting progeny were evaluated for many years to follow. While the pure *C. avellana* plants showed little increase in adaptation over their parents, the hybrids with "Rush" showed promise. In 1951, two superior plants were selected and released: "Potomac", a hybrid of "Rush" × "Duchilly", and "Reed", a hybrid of "Rush" × "Hall's Giant". While both were described as cold-hardy and productive under eastern conditions, neither proved to be of commercial value (Crane and McKay 1951; Reed and Davidson 1958; ASHS Press 1997). "Potomac" was Later reported to be resistant to eastern filbert blight (EFB), while "Reed" was found to be susceptible (Lunde et al. 2000). Both cultivars are available from the NCGR.

2.5.2.3 G.H. Slate

Hazelnut research was initiated in 1925 at the New York State Agricultural Experiment Station in Geneva, New York by G.H. Slate. The early goal was to collect and evaluate a wide range of *C. avellana* cultivars for production in New York; at its largest, the collection held about 120 cultivars imported from Europe, as well as several *C. americana* selections and interspecific hybrids. It became evident that most clones of *C. avellana* were poorly adapted to New York conditions, with staminate flowers and wood proving to be only marginally hardy (Slate 1935, 1936, 1947). Efforts to develop better adapted hazelnuts were initiated in 1930 when Slate first made crosses with "Rush" plants growing in Ithaca, New York, with pollen collected from several *C. avellana* cultivars held in the Geneva collection. Additional crosses with "Rush" were made in Ithaca in 1931 and 1933. In 1932, intraspecific crosses were made at Geneva using "Barcelona" and, to a much lesser extent, "Duchilly" as pistillate parents, crossed with several *C. avellana* cultivars that showed promise in the collection. No additional crosses were made by Slate (1936, 1947). The same year, however, 535 hybrid seedlings were planted that had been derived from crosses made by Reed of the Bureau of Plant Industry in Maryland. In total, nearly 2,000 hybrid seedlings were planted and thoroughly evaluated at the experiment station, of which 1,232 were offspring of "Rush". Plants were evaluated for nut characteristics including size, shell color, kernel quality, and yield, as well as plant growth habit and cold hardiness.

By 1947, 340 of the 2,000 seedlings showed merit and were retained for further observation, with 52 selected for propagation and testing in a new orchard. Nearly all were progeny of "Rush", with only a few progeny of "Barcelona", and no "Rush" × "Winkler" or "Rush" × "Littlepage" hybrids (Slate 1947). In 1961, Slate reported that the performance of the selected hybrids moved to the new orchard, which was more exposed to winds and on poorer soil, was much less satisfactory than in the original planting. Winter injury of the wood and catkins was more serious and crop yields were light, which made evaluations challenging. Furthermore, bud mites infested the orchard to further reduce crops and limit opportunities to evaluate the selections (Ourecky and Slate 1969). By 1980, only 24 of Slate's original selections remained at the experiment station, of which 23 were progeny of "Rush" (Reich 1980). Today, nothing remains of the hazelnut breeding efforts in Geneva; however, a number of Slate's most promising breeding selections are available at the NCGR where they can contribute to future breeding efforts. The drawbacks of using a limited diversity of *C. americana* parents are present in the body of work published by Slate. In addition to bud mite susceptibility inherited from "Rush", most did not release the nuts from the husk on maturity, many were not sufficiently cold-hardy, and they generally produced low numbers of catkins (Slate 1961). After several decades of work, no cultivars were released from Slate's efforts. However, useful EFB-resistant hybrids were developed and identified, and several have been propagated today for backyard use (Earnest Grimo, personal communication, 2010). Several of Slate's selections have been used as EFB-resistant parents in private and public breeding efforts, including advanced generation hybrids at Oregon State University (Molnar et al. 2010). A number of Slate's selections (designated with a New York identification number, i.e. NY616, NY398, etc.) are currently available from the NCGR.

2.5.2.4 S.H. Graham

Also in the 1930s, S.H. Graham of Ithaca, New York continued work pioneered by J.F. Jones. He grew and evaluated hundreds of plants from open-pollinated seeds of Jones' first generation hybrids, including seeds collected from "Bixby" and "Buchanan" growing in close proximity to one another. Graham considered these plants second-generation hybrids, expecting to see an improvement over Jones' work in this apparent next generation. He also grew seedlings of *C. americana* "Winkler" and made his own interspecific hybrids using "Winkler", "Rush", and unnamed interspecific hybrids (Graham 1936). Graham's planting was in a colder area of New York than Geneva, and his trees experienced significant winter injury there. His plantings were also infected by EFB, which was still not present in the research plots at Geneva as late as 1952 (Slate 1952). While Graham (1936) found that a majority of his progeny proved inferior to their parents in nut quality, and it was reported that he lost most of his hybrids to EFB (Slate 1969), two cultivars were named and released from his efforts: "Morningside" ("Rush" × *C. ave.* "Duchilly") in 1945 and "Graham" ("Winkler" × *C. ave.* "Longfellow") in 1950. "Morningside" is reported to have been lost due to EFB (ASHS Press 1997). The status of "Graham" is currently unknown.

2.5.2.5 C. Weschcke

Carl Weschcke also worked to hybridize *C. americana* and *C. avellana* in the 1930s and 1940s. He was a very ambitious nurseryman in River Falls, Wisconsin, interested in northern nut trees, who got his start with hazelnuts in 1921 by ordering one hundred "Rush" hazelnut plants from J.F. Jones' nursery in Pennsylvania. The plants ended up being seedlings of "Rush", instead of clones, and many appeared to be hybrids between *C. americana* and *C. avellana* (Weschcke 1954). The diversity reported in this planting likely sparked Weschcke's interest in hazelnut breeding. In 1927 he planted "Winkler" hazelnuts purchased from a nursery in Iowa, and the following year planted additional Jones hybrid hazels (seedlings of Jones' interspecific hybrids). Then, in 1929, he planted clones of twelve different *C. avellana* cultivars purchased from a New York nursery. Over the next couple of years, most of the Jones hybrids and all the of cultivars of *C. avellana,* which included "Italian Red" and "Medium Long" reported to be cold-hardy by Slate (1959), were killed by cold temperatures, demonstrating the harsh climate of Wisconsin. To continue his project, in 1932, Weschcke planted *C. avellana* selections from J.U. Gellatly of West Bank, British Columbia, which also suffered from winter injury, although they survived for several years. They were of value to Weschcke when he found an exceptional wild *C. americana* plant growing in the woods on his farm. In 1934, he crossed the wild plant with pollen from a surviving Gellatly hazelnut; four cold-hardy hybrid plants were the result, which Weschcke called "hazilberts." Three hybrid plants, possibly from this first cross, were released several years later named "Carlola", "Delores", and "Magdalene". All were listed as having the staminate parent *C. avellana* "Brag" developed by J.U. Gellatly (ASHS Press 1997). None of these plants are known to exist today.

In 1939, Weschcke made crosses between "Winkler" and various *C. avellana* parents. He also crossed his surviving Jones hybrids with pollen from cold-hardy *C. avellana* seedlings from Gellatly. Later, Weschcke found several more exceptional wild hazelnuts in his area that expressed traits such as high yields, large size nuts, early maturity, and thin shells, which he used as female parents in his crosses; from 1942–1945, hundreds of hybrids between *C. americana* and *C. avellana* were produced. Pollen was obtained from other hazelnut growers in the US, or from *C. avellana* surviving on his farm. Staminate parents included "Barcelona", "Duchilly", "Red Aveline", "White Aveline", "Purple Aveline", "Italian Red", "Daviana", and several others. By 1945, he had around 2,000 plants under evaluation and, by 1952, had accumulated extensive data on 650 of them. Weschcke (1954) described that, although there were likely several plants worthy of release in this group, he would prefer to see what is found in the next generation of 1,000 plants. Nearly 10 years later, he reported that his *C. americana* × *C. avellana* hybrids were reliable croppers under all conditions and were bred so that EFB would not be a problem. However, he stated that there was not yet any individual commercially valuable plant, but he expected to recover this in the next 10,000 seedlings he brought into bearing (Weschcke 1963). This expectation never came to fruition, as Weschcke (1970) later reported that most of his hybrids were killed by EFB after all, although he declared that not all of the plants died. He passed away in 1973. After several decades of breeding, no cultivars were released from his work, although his efforts generated better-adapted and EFB-resistant hybrid plant material that has been used in more recent breeding efforts.

2.5.2.6 P. Rutter

Philip Rutter of Canton, Minnesota expanded on Weschcke's work by collecting seeds from select trees of the thousands surviving in Weschcke's overgrown, EFB-infected orchards in River Falls, Wisconsin. In an attempt to identify reliably productive parent plants to initiate his own mass selection program, Rutter collected seeds from EFB-resistant plants of apparent *C. americana* × *C. avellana* origin that were bearing nuts in a year when most plants did not produce crops. He grew the resulting plants on his hilly, windswept farm in south-eastern Minnesota. Rutter later added seedlings originating from various interspecific hybrids developed by G.L. Slate, J.U. Gellatly, and C. Farris, as well as some of his own collections of wild *C. americana* and *C. cornuta*. Inferior plants were eliminated by the harsh climate of Minnesota, the low-maintenance nurseries in which they were grown, and the presence of EFB. In addition to cold hardiness and resistance to EFB, the main breeding objectives were to select plants expressing high kernel productivity and increased cropping potential. Adapted, high-yielding seedlings were identified from these early plantings and their nuts were harvested to plant successive generations to undergo similar evaluations. Pollinations were controlled to some degree by emasculating inferior plants prior to anthesis (Rutter 1987). Today, several generations and over 50,000 seedlings have been cycled through evaluations by Rutter. From this work, he has identified plants expressing EFB resistance and cold hardiness that are segregating for increased nut yields and quality, with mass selection efforts continuing. While no cultivars have been released to date, improved seedling plants have been widely distributed. Experimental plantings of his hybrid seedlings have been established in numerous parts of Minnesota, Nebraska, Wisconsin, and other states. From this germplasm, Hammond (2006) identified several consistently high-yielding selections out of over 5,000 seedlings grown at the Arbor Day Farm in Nebraska City, Nebraska. Based on single-plant estimates, the 4-year average of the highest yielding selection was 4 ton/ha of dried, in-shell nuts. While single-plant extrapolations can be misleading, Hammond's work was done in a tightly spaced orchard with no irrigation, fertility, or pest management, which provides evidence for the potential of select *C. americana* hybrids to produce abundant crops in the Midwest US with little inputs.

Overall, the past work hybridizing *C. americana* and *C. avellana* provided useful genetic resources that are currently available, as well as insight into the direction a plant breeding program may need to go to make the best, most efficient use of this hybrid combination. While the genetic resources used in the early work were limited, some cold-hardy, EFB-resistant plants with relatively large, high-quality nuts were developed. However, not all hybrids were resistant to EFB, and unreliable and occasionally low yields did not warrant commercial production in the east. Most breeding efforts stopped at the first generation, or putative second generation crosses were made by hybridizing within the best of the first generation hybrids, sometimes with no or little control of pollen flow. This approach is largely inefficient and may have further narrowed the genetic diversity present in the hybrid germplasm when plants were grown under the high selection pressure (bottle neck) of severe environmental stress and/or disease pressure. Based on the results of past efforts, a different approach is suggested here. To maintain the high-quality, large kernels, and high yields of *C. avellana*, with the wider adaptation of *C. americana*, a diversity of select *C. americana* parents must be used (parents that compliment their *C. avellana* counterparts) in a systematic, multigenerational breeding effort. Large hybrid progenies must be evaluated in the proper environment to identify the rare recombinants that express the highest levels of desirable traits of each species. The best individuals must then be clonally propagated and tested in multiple locations to identify those with the highest potential for consistent production and for use as improved breeding parents. Advanced generation hybrids must then be made by backcrossing the superior first-generation hybrids to improved, complimentary, and unrelated *C. avellana*. From here, the cycle will likely need to be continued for at least one to several generations to combine the wide adaptation of *C. americana* with the nut qualities of *C. avellana* – in the opinion of the author, a very laudable, but feasible goal.

2.5.3 Corylus heterophylla

The Siberian hazel, *C. heterophylla*, can be found growing across a wide range of climates and soils in Korea, Japan, China, and the Russian Far East. *Corylus heterophylla* crosses readily with *C. avellana* and *C. americana*, although success of seed set depends on the choice of parental clones (Cho 1988; Weijian et al. 1994; Erdogan and Mehlenbacher 2000a). *Corylus heterophylla* is analogous to *C. americana* in many characteristics, including its potential for breeding widely adapted hybrid cultivars, and plants exist that drop the nuts from the involucres at maturity – a rare occurrence in *C. americana*. Compared with cultivated *C. avellana*, the nut is smaller and thicker-shelled and the yield is generally lower. However, plants from its northern range are extremely cold-hardy and drought-tolerant, some being adapted to regions of northeast China that have snowless winters and temperatures dropping below −30°C. Seedlings of the species have been reported to be extremely precocious, sometimes flowering in only 1 or 2 years from seed (Thompson et al. 1996). Cho (1988) reports that this characteristic is also expressed in hybrids of *C. heterophylla* × *C. avellana*. In addition, selections of *C. heterophylla* and its hybrids have also been found to be EFB resistant (Coyne et al. 1998; Chen et al. 2007; Molnar et al. 2010), and *Corylus het.* var. *yunannensis* is adapted to alkaline soils (Thompson et al. 1996). Furthermore, many selections of *C. heterophylla* have distinct, truncated, and variable leaf shapes, which may enhance other ornamental attributes like purple leaf color when used to develop hybrid ornamental landscape plants. The success of the Chinese breeding program, as discussed below, suggests that *C. heterophylla* may be one of the more useful wild *Corylus* species for enhancing the climatic adaptation of commercial hazelnuts. Based on its wide native range, outcrossing nature, and adaptation to varieties of soils and stressful climates, it is expected that considerable genetic diversity exists in the species. Unfortunately, *Corylus* germplasm collections outside of China and Korea contain only a very limited representation of *C. heterophylla*.

2.5.3.1 Economic Forest Research Institute of Liaoning Province, Dalian, China

Traditionally, nuts of *C. heterophylla* have been collected from wild stands for home consumption and local sale across its native range. In the 1960s and 1970s, forest management, including tree thinning, weeding, and pest control, was done in wild hazelnut stands in China to increase production (Weijian et al. 1994). To better meet a growing demand, open-pollinated seeds of several cultivars of *C. avellana* were introduced from Bulgaria, Albania, and Italy between 1972 and 1975, with the resulting plants grown at the Economic Forest Research Institute of Liaoning Province in Dalian, China. The goals were to evaluate the potential of *C. avellana* in China and to select improved individuals suited for commercial production in Liaoning Province. A total of 203 seedlings from these collections were planted. They were quickly found to be sensitive to winter injury in Dalian, which routinely reaches −15 to −20°C during winter months, compounded by high wind and low air humidity in the winter. The poor performance of

C. avellana turned breeders' attentions to the prospect of improving wild *C. heterophylla* growing in northern China.

In 1980, a program was undertaken to evaluate very large numbers of wild *C. heterophylla* growing in Liaoning province for their production potential and nut characteristics. Over the next 5 years, out of many thousands of plants, 31 superior *C. heterophylla* strains were identified that expressed qualities such as high yield, improved nut quality, and thin shells. The most useful plants were propagated and placed in the first *Corylus* germplasm collection in China, which by 1991 contained six species and over 100 cultivars and lines (Weijian et al. 1994). No individual *C. heterophylla* selection was shown to be ideal for commercial production, causing breeders to focus their efforts on creating interspecific hybrids between *C. heterophylla* and *C. avellana*. The first interspecific hybrids were made in 1980. Breeding goals were to develop high-yielding plants that produced the large nuts, high-quality kernels, and thin shells of cultivated *C. avellana*, while expressing the cold hardiness and adaptability of *C. heterophylla*. In their crosses, ten strains of select *C. heterophylla* and 20 of the best *C. avellana* seedlings identified from earlier efforts were used. The pollen of different strains within a species was mixed before making hybridizations, to help ensure seed set. While it was possible to use *C. avellana* as the pistillate parent, the compatibility was much higher when using *C. heterophylla* (Weijian et al. 1994).

From 1980 to 1986 more than 2,300 hybrid progeny were produced and grown in Dalian. Over the next 10 years plants were evaluated for cold hardiness, nut quality, and yield. From these evaluations, around 40 hybrid plants were identified that were superior to the selected strains of pure *C. heterophylla* and were much better adapted than *C. avellana* (Weijian et al. 1994). In 1990, the best 12 of these plants were placed into replicated yield trials in Dalian, Anshan, and Shenyang. From these trials, five superior interspecific hybrid plants were named and released in 1999 for production: "Pingdinghuan", "Bokehong", "Dawei", "Jinling", and "Yuzui" (Ming et al. 2005). Recognizing a need for improved quality nuts, breeding efforts were continued in Dalian. In 2001 and 2003, attempts at second-generation hybrids were made between advanced hybrid selections and several select *C. heterophylla* plants, including collaborations with researchers in Italy (Ming et al. 2005). Although none of these second-generation plants have yet to be released, several more cultivars from the original crosses were released in 2007 and 2008: "Liaozhen 1", "Liaozhen 2", "Liaozhen 3", and "Liaozhen 4" (Ming et al. 2007, 2008; JinLi et al. 2007, 2008). The cultivation of hazelnut in China has increased due to the success of the interspecific hybridization program. Currently, around 1,200 ha of hybrid hazelnuts have been planted in northern China, with production continuing to expand (Liang et al. 2008; FAOstat 2010).

2.5.3.2 Breeding Efforts in Korea

A similar program to that in China was initiated in Korea in 1975 at the Rural Development Administration, as discussed by Mehlenbacher (1991a). Large numbers (more than 40,000) of native *C. heterophylla* and *C. sieboldiana* were evaluated for immediate production or for use in a hybridization program with *C. avellana*. From this work, 35 *C. heterophylla* and 10 *C. sieboldiana* selections were made, several of which are now held at the NCGR, including *C. heterophylla* "Ogyoo" and several numbered selections. A hybridization program was undertaken to combine the adaptation of the native species with the larger, high-quality nuts of *C. avellana* (Cho 1988), resulting in the release of "Poongsil" (*C. heterophylla* × *C. avellana* "Butler"), and "Gaeam No. 1" ("Ogyoo" × *C. avellana* "Butler"). The current status of this program is unknown. Hazelnut research, including a germplasm collection, has also been undertaken at the Institute of Forest Genetics in Korea (Mehlenbacher 1991a; Lee 2002), although recent details are lacking in Western literature.

2.5.3.3 C. Farris

Cecil Farris, a private hazelnut breeder from Lansing, Michigan, was one of the first to hybridize *Corylus heterophylla* with *C. avellana* in the US. He used a single accession of the species *C. heterophylla* var. *sutchuensis* obtained from western China in crosses with pollen of *C. avellana* "Holder" in 1971–1973 (Farris 1974). Farris grew out several dozen seedlings, of which some were dwarf and stunted and others were vigorous and healthy. The progeny appeared to Farris to be true hybrids based on plant morphology; he selected the five best plants and named them Estrella hybrids, numbered 1 through 5. While some of the five selections appeared to have sterility issues, he successfully crossed "Estrella #2" with pollen from *C. avellana* "Royal". All of the offspring appeared to grow normally, demonstrating the ability to backcross the hybrids to *C. avellana*. He also successfully crossed "Estrella #2" with pollen from "Faroka", a *C. colurna* × *C. avellana* interspecific hybrid developed by J.U. Gellatly. "Estrella #1" and "Estrella #2" are available from the NCGR; "Estrella #1" was shown to be resistant to EFB (Chen et al. 2007).

2.5.4 Corylus cornuta

Corylus cornuta is the most cold-hardy *Corylus* species in North America. It grows wild across much of the northern US and southern Canada into regions that reach −50°C. It is also believed to be highly EFB-resistant as there are no reports of this disease occurring on *C. cornuta* even though its range significantly overlaps that of *C. americana*, the native host of *A. anomala*. Coyne et al. (1998) confirmed this resistance through greenhouse inoculations. *Corylus cornuta* also has very early maturing nuts, a trait that is beneficial to regions like Oregon where a rainy season begins in autumn that can significantly interfere with the harvest of late maturing cultivars. This trait is also needed to grow plants for production in northern regions with short growing seasons. *Corylus cornuta* has a very stoloniferous, spreading-growth habit and can form dense thickets, which may prove useful in soil reclamation or for providing wildlife habitat. Conversely, this trait would be a negative attribute in most orchard settings. While Erdogan and Mehlenbacher (2000a) were only able to cross *C. cornuta* with *C. californica*, *C. sieboldiana*, and to a limited degree *C. heterophylla*, Gellatly (1950, 1956) reported success making crosses with *C. avellana* to develop his "Filazel" hybrids.

2.5.4.1 J.U. Gellatly

Gellatly (1950) collected extremely cold-hardy *C. cornuta* from the Peace River District of Alberta, Canada, and hybridized it with his own selections of cold-hardy *C. avellana*, including "Craig" and others. His goal was to combine the extreme cold hardiness and early nut maturity of *C. cornuta* with the large nut size of cultivated *C. avellana*. While he did not use hand pollinations to make the crosses, he was able to select hybrid offspring by identifying seedlings expressing characteristics that were intermediate between the two species (Gellatly 1950; Farris 1990; Thompson et al. 1996). Gellatly distributed seed and plants and released a number of selections of this hybrid cross that include "Peoka", "Manoka", "Fernoka", "Farioka", and "Myoka". "Myoka" is available at the NCGR (2010), while the availability of others is unknown. Mehlenbacher (1991a) and Farris (1990) successfully crossed Filazel #45, a numbered hybrid (*C. cornuta* × *C. avellana*) selection of Gellatly's, with pollen of *C. avellana*. Farris (1990) also reported that pollen of Filazel #45 set nuts on *C. avellana* "Ennis" and the advanced-generation *C. colurna* hybrid "Grand Traverse" and that the early maturity of this selection was expressed in its offspring. While Erdogan and Mehlenbacher (2000a) did not have success with crossing *C. cornuta* and *C. avellana* in either direction, it is possible that when using a wider diversity of germplasm and larger numbers of crosses, poorly understood barriers to interspecific hybridization between *Corylus* species may be overcome and successful hybrid offspring could be generated. In the case of *C. cornuta,* this could strongly assist in developing commercial quality hybrid plants adapted to very cold climates and short growing seasons.

2.5.5 Corylus californica

Corylus californica can be found growing in the coastal mountains of the Pacific Northwest. It has only been utilized to a minor extent due to its small, thick-shelled nuts, which like its very close relative, *C. cornuta*, are very early maturing. This trait, plus its less-stoloniferous growth habit and shorter husks, may make it more useful for breeding, if cold hardiness is not a primary objective. Since the inadvertent introduction of EFB into the Pacific Northwest, it has been observed that *C. californica* growing adjacent to infected orchards remained free of disease. Coyne et al. (1998) confirmed the presence of resistance in the species through greenhouse inoculations. While selections of pure *C. californica* remained free of

EFB, small cankers developed on several *C. californica* × *C. avellana* hybrids. Further supported by additional unpublished work, the performance of *C. californica* × *C. avellana* hybrids indicate that *C. californica* expresses quantitative resistance rather than complete resistance to EFB (Shawn Mehlenbacher, personal communication, 2009). Erdogan and Mehlenbacher (2000a) reported that *C. californica*, when used as a female parent, was able to hybridize with all other species used in their study (Table 2.3), suggesting it may have use as a bridge species to create advanced generation interspecific hybrids.

2.5.6 Corylus sieboldiana

Corylus sieboldiana grows across much of eastern and northern Asia, including the Russian Far East. It is generally very cold-hardy, with many similar traits to *C. cornuta* and *C. californica*, although it has late maturing nuts (Erdogan 1999). Coyne et al. (1998) showed that accessions from Korea were resistant to greenhouse inoculations. Erdogan and Mehlenbacher (2000a) showed that it hybridized readily with *C. cornuta* and *C. californica* and to a much lesser extent with *C. americana*. Reports from Korea, described in Mehlenbacher (1991a), claim that it was hybridized with *C. avellana* to develop better-adapted cold-hardy plants with larger nuts, although little recent information is available on hybrids and few exist in the West for study. A substantial collection of *C. sieboldiana* is available at the NCGR (Table 2.3), which will prove useful to better study the breeding potential and genetic diversity of this species.

2.5.7 Corylus colurna

Corylus colurna, the Turkish tree hazel, is found naturally occurring in the Balkan Peninsula, Turkey, and the Caucuses, but it has been grown widely as an ornamental shade tree in many parts of Europe and the US for centuries. In the landscape, *C. colurna* naturally forms an attractive pyramidal crown and displays interesting scaly, corky bark, and heavily textured leaves. It has been shown to be cold-hardy and exceedingly drought and stress tolerant, with Dirr (1998) suggesting its use as a street tree, even under city conditions. Its small, thick-shelled nuts with high-quality kernels have been collected from the wild and consumed and sold in its native areas, but trees are usually more valued for their excellent timber.

While *C. colurna* remains a single-trunk tree, the shrubby natured *C. avellana* produces suckers from the base of the plant throughout the growing season. To maintain grafted trees of *C. avellana* and to facilitate mechanized production in commercial orchards, suckers must be removed numerous times per year, which requires a significant amount of expense and time. As such, a non-suckering rootstock would be very beneficial to commercial production. Seedlings of *C. colurna* were used as rootstocks for *C. avellana* in the past, including for ornamental forms. However, poor germination rates and transplanting problems due to its less-fibrous tap root system, as well as decreased performance of older nut orchards grafted on *C. colurna*, have reduced its value for such applications (Lagerstedt 1976). Nevertheless, *C. colurna* still holds promise for use in interspecific hybridization programs, especially in terms of developing vigorously growing, stress-tolerant, non-suckering clonal rootstocks (Lagerstedt 1975, 1990).

It is very difficult to hybridize *C. colurna* and *C. avellana*; however, a limited number of fertile hybrids have been created in the past, and are discussed below. More recently, Erdogan and Mehlenbacher (2000a) were able to recover a small number of hybrid seedlings when making large numbers of crosses between *C. colurna* and *C. avellana*. It was shown to hybridize readily with *C. chinensis*, and less successfully with *C. heterophylla* and *C. californica*. They suggest when attempting to make the cross with *C. avellana*, breeders should perform large numbers of pollinations and expect only a small number of hybrid seedlings. In addition to their growth habit and adaptation attributes, select *C. colurna* and *C. colurna* hybrids have also been reported to be resistant to EFB and big bud mites (Coyne et al. 1998; Farris 1978, 2000; Lunde et al. 2000; Chen et al. 2007), suggesting its direct usefulness for breeding improved *Corylus* hybrids.

2.5.7.1 J.U. Gellatly

J.U. Gellatly of West Bank, British Columbia reported some of the first hybrids of *C. colurna* × *C. avellana*, naming the hybrid plants as a group "trazels" (Gellatly 1964, 1966). His plants resulted from the open-pollination of *C. colurna* trees grown in close proximity to trees of *C. avellana,* reportedly "Craig", "Holder", and "Brag". Gellatly grew large seedling populations of *C. colurna*, presumably for rootstocks for his nursery business, and he identified hybrids based on their appearance (Farris 2000). He then evaluated the apparent hybrids for cold hardiness and nut characteristics. After 30 years of work, several superior hybrids and numbered selections were named and released by this method, including "Morrisoka", "Faroka", "Karloka", and "Eastoka" (Gellatly 1966; Farris 1978). These plants were considered to be true hybrids based on their morphology (Erdogan and Mehlenbacher 2000a). These "trazels", as well as several numbered selections of Gellatly's believed to be hybrids between *C. colurna* × *C. avellana*, are held in the collection at the NCGR. Recently, Chen et al. (2007) found several of Gellatly's *C.* hybrids to be highly resistant to EFB, including Chinese Trazel Gellatly #6 and #11 and Turkish Trazel Gellatly #3. While Gellatly refers to the Chinese trazels as hybrids with *C. chinensis* (Gellatly 1966), Chen et al. (2007) believe they are instead *C. colurna*, based on morphology.

2.5.7.2 C. Farris

A continuation of Gellatly's "trazel" work was undertaken by C. Farris of Lansing, Michigan. Farris, a self-trained plant breeder, grew and evaluated most of Gellatly's hybrid selections and considered "Morrisoka" and "Faroka" the best of the group. While the hybrid cultivars were not suitable for commercial production, he believed they would make superior breeding parents based on their cold hardiness, productivity, and high nut quality. His goals were to develop non-suckering, EFB-resistant, cold-hardy plants that produced high-quality, large kernels. Throughout the 1970s and early 1980s, Farris, used controlled hand pollinations to successfully cross "Morrisoka" and "Faroka" with pollen of *C. avellana* "Royal", which has large size nuts, to create advanced-generation hybrid progeny. Pollen of "Faroka" was also used successfully on *C. colurna*, demonstrating the cross-compatibility of Gellatly's first-generation hybrids (Farris 1978, 1982). It should be noted that this fact was reinforced by Thompson et al. (1996) with the successful crossing of *C. avellana* "Willamette" with pollen of "Faroka", as well as successfully making the reciprocal cross with a mixture of *C. avellana* pollens. From his crosses, Farris identified a number of advanced-generation hybrids useful for further breeding or eventual release (Farris 2000). The most widely recognized was his EFB-resistant "Grand Traverse", which he described as a cross between "Faroka" × "Royal" (Farris 1989), although the identity of the *C. avellana* parent is somewhat unclear, based on incompatibility alleles (Lunde et al. 2000). "Grand Traverse" was recently shown to be completely resistant to more than 12 different *A. anomala* isolates collected around the eastern US (Molnar et al. 2010). It was also shown to transmit its resistance to about 25% of its offspring (Molnar et al. 2009), and work is underway to better understand inheritance of the resistance. In 2008, "Grand Traverse" was successfully backcrossed to *C. colurna* and several *C. avellana*, with high cluster set and typical germination (T. Molnar, unreported). Farris (1990) later released "Lisa", an open-pollinated selection of "Grand Traverse", believed to be backcrossed to *C. avellana*. It was also shown to be resistant to EFB, as well as bud mites (Chen et al. 2007). "Grand Traverse" and several others of Farris' selections are available at the NCGR. "Lisa" is held in the collection at OSU.

2.5.7.3 H.B. Lagerstedt

In search of non-suckering rootstocks for use in commercial hazelnut orchards in Oregon, H.B. Lagerstedt initiated a sizable rootstock evaluation and breeding program at Oregon State University, starting in 1968. Lagerstedt organized a collection of 19 of Gellatly's hybrid trazels, as well as five non-suckering selections of possible rootstock potential from Farris. He also included apparent hybrid plants from O. Jemtegaard, who selected the open-pollinated hybrid "Filcorn" by similar means as Gellatly. Lagerstedt grew more than 1,000 open-pollinated seedlings of "Filcorn", which was growing in a *C. avellana* orchard far away from other *C. colurna*, and from this isolation were assumed to be advanced-generation backcross hybrids. From these, he selected 70 plants for further testing (Lagerstedt 1975, 1976). Wide collections were also made from botanical gardens, arboreta, and nurseries in the US, Canada, and Europe (Thompson et al.

1996). Seedlings were evaluated for vigor and non-suckering growth habit. The challenge and expense of identifying an appropriate non-suckering rootstock is substantial. This is due to the need for the plant, once identified as a potential candidate, to first be reproduced on its own roots by layering, which can take several years. Then, it must be evaluated in replicated clonal yield trials, grafted to known cultivars, in comparison to those cultivars growing on their own roots to prove there is not a reduction of yield as a consequence of its use. Finally, in 1990, two rootstock cultivars were released by OSU: “Newberg” (tested as USOR 1-71) and “Dundee” (tested as USOR 15-71). They were selected from a nursery planting in 1971 that contained several thousand open-pollinated seedlings of *C. colurna* (Lagerstedt 1990). Unfortunately, both are highly susceptible to EFB.

Lagerstedt also had a goal to incorporate red leaf color into a non-suckering rootstock that would facilitate maintenance and help differentiate the scion portion from the rootstock portion of a grafted tree. While working on this objective, he developed and released the ornamental hybrid “Ruby”. “Ruby” was derived form a controlled cross between Chinese trazel #4 (believed to be a *C. colurna* × *C. avellana* hybrid) and the red-leaf *C. avellana* “Fusco Rubra”. “Ruby” was selected because it retained its red color longer into the summer than other available red-leaf ornamental hazelnuts (Lagerstedt 1990). In 1984, a red-leaf full-sibling of “Ruby”, USOR24-82, was crossed with a red-leaf breeding selection, *C. avellana* OSU A-28, by M. Thompson and D. Smith. From the resulting progeny, an advanced-generation, ornamental, interspecific hybrid “Rosita” was selected and released in 1999 (Smith and Mehlenbacher 2002).

2.5.8 Corylus jacquemontii

Corylus jacquemontii is very poorly represented in western germplasm collection, research, and breeding efforts. Its genetic diversity and potential for breeding have not been evaluated. The species’ inclusion in recent taxonomic studies has been based on only one or two genotypes available in western collections (Erdogan and Mehlenbacher 2000b; Forest and Bruneau 2000; Whitcher and Wen 2001). Sharma and Kumar (2001) describe efforts to evaluate purported selections of *C. jacquemontii* growing in northwestern India, stressing its underutilized nature. Based on its growth habit, potential uses of this species are as a non-suckering rootstock and as an ornamental shade tree. The species was shown to be susceptible to EFB by Coyne et al. (1998), with all seven accessions succumbing to the disease. Farris (2000) described *C. jacquemontii* succumbing to EFB in Michigan; however, these findings were based on a very limited sample of plant material. In 2008, a seedling tree at the Dawes Arboretum in Newark, Ohio (accession D1997-0030.002) was observed by the author growing completely free of disease while adjacent to several heavily EFB-infected *C. avellana* plants.

2.5.9 Corylus chinensis

Corylus chinensis is also very poorly represented in Western germplasm collections and breeding efforts, and it is considered endangered in China (Sun 1998). Based on its growth habit, it may have direct use as a rootstock or in the development of interspecific hybrids to develop improved non-suckering rootstocks. Based on experience with small seed lots imported from China, seedlings grow more vigorously and with a more fibrous root systems than *C. colurna* (an issue limiting the production of *C. colurna* in the nursery trade). However, based on its region of origin, the species is likely less cold hardy. It would also have use as an ornamental shade and timber tree due to its vigorous growth habit; large mature size; oversized, attractive leaves; and interesting involucres. Seedling *C. chinensis* trees growing at Rutgers University in New Jersey appear to express a high level of resistance to EFB, being disease-free after more than 6 years of exposure (T. Molnar, unpublished). Interestingly, they also appear to be highly resistant to feeding damage done by Japanese beetles (*Popillia japonica* Newman), a common, and often severe, pest problem of hazelnuts grown in the eastern US.

While accessions of *C. chinensis* were limited, Erdogan and Mehlenbacher (2000a) successfully crossed it with *C. colurna*, *C. avellana*, *C. americana*, and *C. californica*. The cross with *C. avellana*, although only with *C. avellana* as the pollen parent, was notable in that it produced the most vigorous offspring out of all the various hybrid combinations in their comprehensive study. This finding strongly suggests that hybrids of *C. chinensis* and *C. avellana* may be useful for developing vigorous non-suckering rootstocks.

2.5.10 Corylus fargesii

Corylus fargesii, also known as *C. papyraceae*, is native to southern China and has only recently been introduced to the West. Its genetic diversity and potential for breeding has not been fully evaluated. Wider collection efforts and preservation in germplasm repositories and botanical gardens is urgently needed. The earliest reported introduction to the US was made by Cecil Farris in 1982 from southern Gansu Province, China. Farris imported 50 seeds, but only recovered three seedlings (Farris 1995, 2000). More recent seed introductions were made by members of the North American China Plant Exploration Consortium in 1996 and 2005, leading to the establishment of *C. fargesii* at a number of US arboreta, the NCGR, and Rutgers University (Aiello and Dillard 2007). Its unique qualities include a single-trunk habit, vigorous growth, and very attractive peeling bark, which resembles that of river birch. Aiello and Dillard (2007) believe that, with improved propagation techniques, *C. fargesii* has merit to become a valuable ornamental shade tree in the central and eastern US. It may also hold value as a non-suckering rootstock, as seedlings grow very rapidly, are easily transplanted, and appear graft-compatible with *C. avellana*. Furthermore, Farris reports his introductions were resistant to EFB after many years of exposure (Farris 1995). Trees located at the Morris Arboretum in Philadelphia, Pennsylvania and Rutgers University in North Brunswick, New Jersey, also appear resistant to EFB, as plants are healthy and without symptoms while growing adjacent to heavily infected *C. avellana* for many years (Aiello and Dillard 2007; T. Molnar, unpublished).

Farris reported successfully crossing *C. fargesii* with "Morrisoka" (*C. colurna* × *C. avellana*) in 1992, with all offspring inheriting the peeling bark characteristic (Farris 2000). No further reports of use in breeding have been made, although investigations are underway at OSU and Rutgers. *Corylus fargesii* is native to relatively warm areas of southern China, so its cold hardiness may be questionable. It also produces small, thick-shelled nuts that are tightly enclosed in the involucre. Therefore, its use in genetic improvement may be limited to developing vigorous non-suckering rootstocks and attractive ornamentals with peeling bark for warmer climates, unless cold-hardy complimentary breeding parents are used. The mode of inheritance of EFB resistance in *C. fargesii* has not yet been investigated.

2.5.11 Corylus ferox

Corylus ferox and *C. ferox* var. *tibetica* are poorly represented in Western germplasm collections and research efforts. It is a small, single-trunk tree native to high elevations with mild climates in the eastern Himalayan Mountains across to parts of Yunnan, Sichang and Xizang provinces in China. The most distinctive feature of this species is its chestnut-like involucre. Farris (2000) suggested that the involucre could protect the nuts from bird and rodent predation until the nuts are mature and ready to fall. He grew a very limited number of *C. ferox* var. *tibetica* accessions in Michigan and found it sensitive to cold damage. He was able to maintain the plants in large pots in his garage to survive the winter. He reportedly crossed *C. ferox* with "Lisa", an advanced-generation *C. colurna* × *C. avellana* hybrid. However, the fate of the hybrid seedlings is unknown. Based on rDNA ITS sequence data, *C. ferox* was separated from all the other *Corylus* taxa (Erdogan and Mehlenbacher 2000b). A much wider diversity of *C. ferox* needs to be collected and evaluated for breeding and research, especially for studies of genetic diversity and the origin and evolution of *Corylus* and the family Betulaceae, based on its possible ancestral taxonomic position.

2.6 Alternative Uses of Wild *Corylus*

Access to an increased diversity of wild germplasm and its systematic use in an interspecific hybridization program should lead to the development of widely adapted plants that can produce crops over a much greater area. This increased production would support the development of new market applications and opportunities, including ornamental plants, feedstock for biodiesel or other oleochemicals, value-added health and food products, animal feed, and other potential areas like soil reclamation, biomass production, and others not yet investigated.

2.6.1 Hazelnut Oil

Hazelnut kernels have a high oil content by weight, with most containing over 60% oil and some up to 70%. The oil is rich in monounsaturated fatty acids, especially oleic acid (around 75–80%), and to a lesser degree linoleic acid (Botta et al. 1994; Ebrahem et al. 1994; Benitez-Sánchez et al. 2003; Xu et al. 2007). Recent work at the University of Nebraska, Lincoln, has demonstrated an alternative potential of hybrid hazelnuts as a low-input feedstock for the production of biodiesel and other valuable oleochemicals. Based on the 3-year average production of their highest-yielding hybrid hazelnut selections, Hammond (2006) estimated that an equivalent of 4-ton/ha of in-shell nuts could be produced. Based on the kernel oil content and shelling percentage of these selections, an oil yield of 1,000 kg/ha – nearly double the yield per hectare of soybean oil (around 500 kg/ha) (FAOStat 2010) – could be realized (Xu et al. 2007; Xu and Hanna 2009, 2010). While single-plant extrapolations can be unreliable, the estimates made by Hammond (2006) and Xu et al. (2007) are not far from the oil yields that could be produced commercially in the Willamette Valley of Oregon, under current production systems, if the kernels were processed for oil. Calculations suggest that nearly 900 kg of oil per hectare could be produced, based on the past 10-year average hazelnut yield data using the cultivar "Casina", which has a shelling percentage of 56% and kernel oil content of 65.3% (Ebrahem et al. 1994; Mehlenbacher 2003; FAOStat 2010).

In addition to its high yield potential, hazelnut oil has a unique fatty acid composition (high monounsaturated fatty acids and small percentages of saturated and polyunsaturated acids), thermal stability, and low temperature properties that should increase its value over soybean oil for a number of applications (Xu et al. 2007; Xu and Hanna 2009). Xu and Hanna (2009) synthesized and characterized biodiesel from hybrid hazelnut harvested in Nebraska and found it to be an excellent feedstock for making the fuel. Similar findings were reported by Gumus (2008) when he synthesized hazelnut-oil based biodiesel and examined its performance in diesel engines in Turkey. While the economics need to be fully examined before it is suggested that hazelnuts be grown as a sustainable source of biodiesel, it should be mentioned that high-yielding, well-adapted, early-generation interspecific hybrids that may not have nut qualities acceptable for the kernel trade (round, high-quality, well-blanching kernels) may find a direct role in oil production where these characteristics are not important. Plus, they can be grown on sloping and marginal land not suitable to annual oil crops.

Besides industrial applications, hazelnut oil, which is very similar in composition to olive oil (Benitez-Sánchez et al. 2003), can likely play a larger role in the diets of humans. A comprehensive review of hazelnut (*C. avellana*) kernel composition and their reported health effects can be found in Alasalvar et al. (2009a). In general, *C. avellana* hazelnut kernels by weight are 58–64% fat, 15–18% carbohydrate, and 10–16% protein. They also contain a total of 24 minerals (essential and non-essential), with potassium the most abundant, as well as the fat soluble vitamins A, E, and K and water-soluble vitamins thiamin, riboflavin, niacin, pantothenic acid, folate, and several others. The kernels are especially high in vitamin E, biotin, and folate, which may be attributed to their reported health-promoting effects. Their fatty acid composition contains a small amount of saturated fatty acids (7–9%) and consists primarily of the mono-unsaturated fatty acids – oleic acid (77–83%) and linoleic acid (7–14%). This ratio of low saturated fatty acids to high unsaturated fatty acids has also been attributed to the health-promoting effects of hazelnuts, especially on human plasma lipid profiles. In addition, Erener et al. (2007) found that the consumption of hazelnut oil by broiler chickens increased oleic acid content of the meat, compared to those fed soybean oil, and that the ratio of saturated fatty acid to mono-unsaturated fatty acid was decreased. While more study is needed, these results suggest hazelnut oil could be used as an animal feed supplement to produce healthier meat products containing a higher level of oleic acids important for human diets. Additionally, the protein meal remaining after oil extraction may add substantial secondary value to oil production, as animal feed or in other products such as baked goods or supplement bars. However, the use of hazelnut protein in this manner has not yet been evaluated.

2.6.2 Potential Phytochemicals and Other Products

There are a number of potentially valuable by-products that would become more widely available with the increased production of hazelnuts production that would become more widely available with increased production. A majority of the world's crop (90% or more) is cracked and sold as some form of raw or roasted kernels. This leaves behind the shell (50% or more of the crop weight), as well as the leafy involucre that surrounds the nuts, especially in Turkey where nuts still in the involucre are harvested by hand. Shells are commonly used directly as a fuel source, many times to aid in the kernel drying process, and shells and involucres can also be used as a compost material. Özcelik and Pekşen (2007) demonstrated the usefulness of the involucres as a component of a substrate to cultivate shiitake mushrooms [*Lentinula elodes* (Berk.) Pegler]. Production also results in a significant amount of biomass from orchards in the form of tree prunings and leaves. Finding higher value use of the by-products of production would provide further economic incentives to grow this low-input crop. While little work has been done to examine possible phytochemicals and other useful compounds in wild *Corylus*, Alasalvar et al. (2009b), in a comprehensive review of existing studies, showed that *C. avellana* kernels, pellicle, shell, involucre, and leaves are a rich source of proanthocyanidins, phenolic compounds, total antioxidant activity, and flavonoids. The pellicle of hazelnut showed the highest level of antioxidant activity compared to other tissues examined and was considered to be a potential industrial source of antioxidants. Furthermore, Oliveira et al. (2007) demonstrated antimicrobial activities of *C. avellana* leaf extracts, suggesting they may be a good candidate as an agent to control bacteria that cause gastrointestinal and respiratory tract infections in humans. In addition, hazelnut by-products also contain low concentrations of paclitaxel and other taxanes (compounds in the widely used cancer drug Taxol) (Hoffman et al. 1998; Hoffman and Shahidi 2009). While concentrations of taxanes in *C. avellana* appear uneconomically low compared to the bark of Pacific yew (*Taxus brevifolia* Nutt) from which it is currently extracted, it is possible that these valuable compounds may be found in higher levels in other *Corylus* species and interspecific hybrids that have yet to be assayed for the compounds. This point can also be applied to all of the other compounds studied for *C. avellana* that have not yet been investigated in wild species.

2.6.3 Ornamental Landscape Plants

A number of highly ornamental traits exist in *C. avellana*, including the weeping habit of "Pendula" and the contorted growth of "Contorta" (also known as "Harry Lauder's Walking stick"). "Rote Zeller", "Fusco Rubra", "Purple Aveline", and "Syrena" exhibit dark red/purple leaves in the spring and early summer, while the bright yellow leaves of "Aurea" and the highly dissected leaves of "Cutleaf" also have promising ornamental value. Unfortunately, all of these cultivars are highly susceptible to EFB, which significantly limits their use in North America. Excluding the weeping habit, the inheritance of these ornamental traits has been studied and most appear to be simply inherited (Thompson et al. 1996). By developing ornamental plants with EFB resistance, whether through *C. avellana* or other species, hazelnuts could be much more widely utilized in the landscape as ornamentals or even as ornamental garden plants as the plants could still produce nuts. Incorporating genes for extreme cold hardiness would further increase their range of usefulness. A number of wild species also express traits, which would make them directly useful as ornamentals or as parents in interspecific breeding programs. For example, some selections of *C. americana* express bright pink or red fall color that is absent in most other species. While the inheritance of fall color in *Corylus* is not well understood, some hybrids of *C. americana* × *C. avellana* express fall color, and through use of select parents, it has been possible to combine the red spring and summer leaf color of *C. avellana* with the EFB-resistance and bright red fall color of *C. americana* (T. Molnar, unpublished). The truncated and variable leaf shapes of *C. heterophylla* would further add to the ornamental attributes of such an interspecific hybrid. The tree hazels offer opportunities to develop improved shade trees that would add interest and diversity to current landscape designs, particularly if incorporated with attractive leaf shape and color traits. Interspecific hybridization offers a means to develop a wide diversity of plant shapes and forms, including those with attractive corky and peeling bark as in *C. colurna* and *C. fargesii*, respectively. Similar to breeding for nut production, the lack of breeding efforts in *Corylus*, especially for ornamental attributes, as well as wider access to genetic resources and the increased understanding of interspecific hybridization potentials and inheritance of traits, should provide opportunities to develop a wide variety of useful, multi-purpose, attractive, landscape plants well into the future.

2.7 Recommendations for Future Conservation, Research, and Genetic Improvement

The diversity and richness of the *Corylus* genus, its usefulness to man, and its importance to natural ecosystems are substantial. Increased efforts should be made to preserve, study, and utilize *Corylus* genetic resources for the betterment of future generations. In general, hazelnuts are a very low-input, high-value crop adapted to a wide variety of climates and soils, the production of which has many economic and ecological benefits. Furthermore, recent epidemiological and clinical studies have provided strong evidence that frequent tree nut consumption, including hazelnuts, is associated with favorable plasma lipid profiles and a reduced risk of heart disease, cancers, strokes, inflammation, and other chronic health issues (Alasalvar and Shahidi 2009). These positive economic, environmental, and health factors are driving increased production and market demand worldwide. World production acreage has increased almost 14% over the past 10 years (Fideghelli and De Salvador 2009). The development of more widely adapted cultivars would provide greater options for farmers to help meet this increasing demand. As discussed at length in this chapter, *Corylus* genetic resources are highly underutilized and underrepresented in research studies and conservation efforts, germplasm collections, and breeding programs. Aside from cultivated forms of *C. avellana*, little is known of their genetic diversity and population structure, with possible unchecked genetic erosion occurring due to overdevelopment, deforestation, and other causes. Molecular biology tools are now available for *Corylus*, including a multitude of effective SSR markers (Gürcan et al. 2010), that can be utilized to assess genetic diversity in wild species and also fingerprint accessions to reduce duplication in germplasm collections and show gaps in collections. A more thorough and accessible catalog of wild *Corylus* germplasm existing at research institutions, botanical gardens, and arboreta – similar to that currently conducted by the "Safenut" project in Europe for cultivated *C. avellana* (Bacchetta et al. 2009) – should be compiled and made available to hazelnut researchers worldwide. Besides obvious species deficits in Western collections such as *C. jacquemontii*, *C. ferox*, and *C. fargesii*, collections are also deficient in plants of the more common species originating from their most northern and southern ranges. Collections from these areas would be extremely valuable for expanding production of cultivated hazelnuts into more stressful climates. Efforts are needed to collect and evaluate this germplasm, with the most useful selections preserved and made widely accessible to world germplasm banks.

In the past, *Corylus* genetic improvement efforts demonstrated that significant progress can be made through breeding; moving forward, however, a multi-generational approach should be followed, and the enhancement of genetic diversity in breeding lines should be stressed. Molecular biology tools must be used in concert with breeding efforts to ensure this is the case. The lack of diversity used in the interspecific hybrids made with *C. americana* and *C. avellana* in the first half of the twentieth century exemplifies this point. While *C. americana* "Rush" produced large size nuts for the species, many of its negative attributes were also transmitted to its offspring, which included a lack of significant cold hardiness, high susceptibility to bud mites, nuts that are retained in the husk at maturity, and a reduced numbers of catkins (Slate 1961). Besides the lack of diversity, most crosses were also limited to first-generation hybrids. The recent breeding progress at OSU clearly demonstrates the potential for substantial improvement in the second and third generation of breeding (Mehlenbacher et al. 2007, 2008, 2009). Selecting a wide diversity of the best, complimentary *C. avellana* parents available is especially important when using a modified backcross program to incorporate characteristics from wild species. Fortunately, much wider access to cultivated forms of *C. avellana* is available now than in the past. Additionally, the ability to ship pollen overnight from almost anywhere in the world makes it is possible to use parents in breeding efforts that would not typically grow in the location of the breeding program, providing a very efficient means to exchange genetic resources. For example, pollen from EFB-susceptible, *C. avellana* cultivars and breeding selections with high-yields and excellent nut quality is routinely shipped from OSU and the NCGR to use in controlled crosses at Rutgers University in New Jersey, to develop improved, locally adapted selections. Many of these parents would not survive long enough in New Jersey to use in crosses due to EFB and the colder climate. In addition, pollen carries few viruses or diseases, reducing concerns related to the importation of seeds or clonal material. For a description on pollen collection and handling see Thompson et al. (1996).

Exciting opportunities now exist to study and more widely utilize the *Corylus* genus. Rapid genetic gains are expected in breeding, based on its highly heterozygous nature, the ability to hybridize numerous species, and very limited prior breeding efforts. In the opinion of the author, the wild species of most immediate value for breeding improved interspecific cultivated forms (backcrossed to *C. avellana*) are *C. americana* and *C. heterophylla*. These both cross readily with *C. avellana* and are adapted to a wide climatic range with those from the northern areas being extremely cold-hardy. Selections of *C. americana* and *C. heterophylla* are also resistant to EFB, although inheritance is not well understood in these species, and some plants are very precocious and high yielding. A number of first-generation hybrids already exist in the US and China that can play an integral role in developing the foundation for developing advanced-generation hybrids. The collection and evaluation of a larger variety of wild germplasm will likely lead to the identification of more diverse improved selections to be used in long-term breeding efforts. Other *Corylus* species merit much wider collection and study for the conservation of genetic resources and for use in breeding, to enhance genetic diversity in cultivated forms, and to donate specific traits of interest such as extreme cold hardiness, drought tolerance, non-suckering growth habit, ornamental attributes, disease and pest resistances, and other characteristics that arise as more is learned about the wild species and as market demands dictate.

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