Section 6
Experimentation and current distribution

CHAPTER 6.1.1

Adaptation and scope for quinoa in northern latitudes of Europe

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Abstract

Quinoa (*Chenopodium quinoa* Willd.) is a new crop, currently being tested in northern Europe, where its close relative, fat hen (*C. album*), is already a well-known weed species. During the Iron Age, European fat hen was a secondary crop, either collected or cultivated. Therefore, the present day introduction of quinoa to northern Europe is based on the utilization of a closely related species in ancient times. Quinoa is one of the oldest existing crops, and was first detected by Europeans when Columbus discovered South America at the beginning of the sixteenth century. Quinoa was not then brought to Europe, however, so the crop literally remained unknown outside the Andean countries until North Americans came to Bolivia and Peru in the late 1970s in order to import quinoa as a food product to the United States of America. Quinoa was at that time also introduced to the United Kingdom, Denmark and the Netherlands, where studies on the crop were initiated, to be later followed by trials elsewhere in Europe and the rest of the world. Nevertheless, there is at present very little commercial production of quinoa outside the Andes; but it is increasing, and there is good potential for further expansion of global production. According to FAO, quinoa is regarded as a new world staple and is predicted to spread fast across the globe (FAO, 2013). Due to the increasing global demand for quinoa, both as an Andean export commodity and for agricultural development purposes, there is huge interest in testing quinoa for cultivation under a range of environmental and geographical conditions. One of the environments most distanced from the crop's natural conditions is northern Europe. Research carried out in Europe, from south to north, has demonstrated the potential of quinoa for production under European conditions, with varieties adapted to longer days, increased humidity and intensive mechanization. Most recently, quinoa has successfully been grown commercially in Australia and France, and is on the verge of taking the same step in a number of other countries.

Introduction

The *Chenopodium* genus comprises around 250 species from all over the world. It is considered one of the most nutritious genera in existence, due to its protein and dietary fibre content, as well as healthy levels of fat, ash and minerals (Repo-Carrasco *et al*., 2003). Several species of *Chenopodium* have been independently domesticated. Most domestic forms of *Chenopodium* are grown as seed crops, for example, *C. pallidicaule*, although others, such as *C. nuttalliae* in Central America, are also used as a spinach-like vegetable. The oldest domesticated

Chenopodium species identified to date is the South American quinoa, developed in the Andes about 7 500 years ago (Pearsall, 1992). It reached North America in around 1200 A.D. Other species were independently domesticated, rather than being spread by trade.

In northern Europe, *C. album*, a global weed species, was a secondary crop in Denmark during the Iron Age (1200 B.C. – 400 A.D.) (Stokes and Rowley-Conwy, 2002). Various prehistoric finds from Denmark, such as a deposit of 1.5 litres of seeds, calculated to comprise 2.4 million seeds, from the first few centuries A.D., demonstrate the separate gathering or cultivation of this species for food (Helbaek, 1954). Seeds of *C. album* were also present in the stomach contents of the bog bodies from Tollund (Helbaek, 1950) and Grauballe (Helbaek, 1958). The plants for these meals were probably deliberately harvested by Iron Age farmers, who collected the whole plant for subsequent threshing and drying (Glob, 1969). *C. album* seeds are also known to have been used at the site of Voldtofte, Denmark, due to finds from as early as the Late Bronze Age (1570–1200 B.C.) (Rowley-Conwy, 1982, 2000).

C. album was also used as pasture for milking cows in Denmark during the Second World War (1940–45), as farmers discovered that it secured good milk production. The question is whether the Danish and European adaptation of *Chenopodium* should concentrate on *C. album* or *C. quinoa.* It was decided to focus on quinoa, as it is a long journey to transfer a wild species, such as *C. album*, to a crop (Risi and Galwey, 1984, 1989a; Jacobsen, 1997). Although quinoa is a tropical crop, it is also a highland crop and grows at relatively low temperatures.

Crop adaptation

It is necessary to adapt well-known crops to a range of stress factors, both abiotic and biotic, some of which are aggravated by actual and predicted climate changes. These stresses will necessitate the search for adaptation to photoperiods of new regions, especially in crops with good tolerance to stresses, such as quinoa. The standard approach for adaptation of crop species and cultivars to new day lengths and thermal environments has been to manipulate flowering to match phenology with specific climatic conditions, and to regulate the number of days of the plant growth cycle spent in vegetative and reproductive stages (Bertero *et al*., 1999; Lawn, 1989; Lawn *et al*., 1995).

Quinoa might be used for crop diversification in Europe and other parts of the world, outside its genetic origin, as an alternative for marginal agricultural land. For this reason, it has to be adapted to new regions of the world outside the Andes.

Historically, quinoa has been continuously selected for new environments in the Andean region, as it spread gradually from its centre of origin around the Titicaca Lake between Peru and Bolivia. The distribution from the lake went both northwards to Ecuador, Colombia and Venezuela, and southwards to Chile and Argentina, as well as down from the highlands to the valleys and coastal regions of the Andean countries. It was a slow process, however, due to the vast range of environments and the irregular climatic conditions in the Andean region (Bertero *et al*., 2004).

The present adaptation of quinoa to new environments has been relatively fast. No other crop has been introduced as rapidly. The introduction of potato, which was brought to Europe when the Spanish invaded South America in the early sixteenth century and was rapidly distributed throughout Europe, was not accepted commercially until 200 years later, around the start of the industrial revolution in late eighteenth century (Chapman, 2013). Soybean originated in China, and soon spread to Southeast Asia under the Ming Dynasty (Hancock, 2004). It arrived in Europe and America in the eighteenth century, but it did not become important outside Asia until the twentieth century (Hymowitz and Harlan, 1983).

Kiwi fruit is another story of a recent global success. It originated in China under the name “Chinese gooseberry”, and in the early twentieth century spread to New Zealand and was then exported to the United States of America just after the Second World War under its new name (Ferguson, 1999). For quinoa, just 50 years ago, no attention was paid to the species, not even in the Andean region, and no development, breeding or scientific research was being carried out. Quinoa was of value solely to the Andean farmers, while in urban areas it was considered a whole grain of inferior quality (Vietmayer, 1989).

In the past, introduced crops took as long as 200 years to attain acceptance and popularity on a broad scale (potato and soybean), while the kiwi fruit managed the same process in only 50 years. Quinoa has so far taken approximately 30 years, and it is close to a global success.

All stages of development in quinoa are sensitive to changes in photoperiod, but in particular the reproductive phase (Bertero *et al*., 1999). Day lengths over 12 hours produce major detrimental effects on the development of quinoa (Christiansen *et al*., 2010). The most important effects of an extended photoperiod are seen after flowering as the seed fill and maturation stages are disrupted, hindering continued vegetative growth and flowering (Bertero *et al*., 1999, 2004; Christiansen *et al*., 2010). This makes quinoa a facultative short-day plant (Bertero *et al*., 1999; Christiansen *et al*., 2010), which means that flowering occurs under any photoperiod, while reproductive development is inhibited by photoperiods longer than those found in its place of origin (Bertero *et al*., 1999, 2004; Christiansen *et al*., 2010). It is recommended to study the physiology, as well as the photoperiod effects (Christiansen *et al*., 2010).

Quinoa has great potential for production in Europe (Galwey, 1993; Jacobsen, 1997; Jacobsen and Stølen, 1993). However, regions interested in introducing quinoa have longer days than those in its centre of origin, and it is, therefore, necessary to carry out studies on physiological mechanisms and photoperiod responses (Adolf *et al*., 2012).

European quinoa history

Quinoa research breeding programmes were not initiated until the 1960s in the Andean countries (McElhinny *et al*., 2007). There were some early attempts in Europe to introduce quinoa, but the genotypes of quinoa screened originated from Bolivia and Peru and, therefore, did not mature at high latitudes (Simmonds, 1965). Breeding programmes outside the Andes were initiated in the United States of America and Europe in the 1980s, with the objective of adapting quinoa in terms of early maturity under new climatic and agronomic conditions.

Quinoa's introduction to Europe began in the 1970s, when it was brought to the United Kingdom following recollection expeditions to South America. A breeding programme was initiated at Cambridge University (Fleming and Galwey, 1995; Galwey, 1989; Risi and Galwey, 1984, 1989a, b, 1991). In 1987, the programme was continued in Denmark after the establishment of collaboration between Galwey and Jacobsen (Jacobsen and Risi, 2001). Both countries worked on a broad range of genotypes obtained from earlier British recollections. Uniform lines were developed and given identification codes, but no varieties were registered. Quinoa breeding in the Netherlands began in 1986 based on accessions from gene banks, botanical gardens and universities. After evaluation, uniform lines adapted to the climate of Western Europe were selected (Mastebroek *et al*., 2002). A stability analysis of the selection time for some quantitative traits of quinoa concluded that height, inflorescence, size and stage of development could be satisfactorily performed in the early stages of a breeding programme, and potential parental lines were identified in one population (i.e. from 14 lines grown during five seasons) for their use in the development of new varieties suitable for north European conditions (Jacobsen *et al*., 1996). In 1993, a project was supported by the European Union, entitled "Quinoa - A multipurpose crop for EC's agricultural diversification", with field trials in the United Kingdom, Denmark, the Netherlands and Italy (Galwey, 1993). Other countries showing an interest in the crop at that time, in the light of the promising results of the EU project, were Sweden, Poland, Czech Republic, Austria and Greece, who all participated in the American and European Test of Quinoa, supported by FAO (Izquierdo *et al*., 2003; Jacobsen, 2003; Iliadis *et al*., 1997, 2001; Ohlsson, 1997). Finland also had trials ongoing (Keskitalo, 1997). Results from the American and European Test of Quinoa showed that the growth period in southern Europe was 100–116 days for the varieties which were able to mature, which is less than the growth period of 110–180 days in northern Europe (Mujica *et al*., 2001).

In the United Kingdom, quinoa is sold in health food shops, but its main application is as a game-cover crop, alone or mixed with kale. A blend of early-, medium- and late-maturing types of quinoa is sown, mainly for pheasants and partridges, causing natural seed drop throughout the hunting season from October to January (Nicholls, 1996). Quinoa seed for game crops is grown successfully in south-east England. More recently, in Denmark, there has been attention on quinoa for people with coeliac disease as a potential alternative to the cereals, wheat, rye and barley, which all contain gluten (Jacobsen, 1997; Jacobsen and Bach, 1998; Jacobsen and Stølen, 1993; Jacobsen *et al.*, 1994, 1996, 1997; Lomholt, 1996). In addition, projects on the production of green pellets from quinoa have been conducted. There is no commercial production of quinoa in Denmark, and Danish consumers currently pay approximately EUR10/kg for quinoa imported from Bolivia. In Denmark and Sweden, yields have been low (if harvested at all), with only European and Chilean varieties maturing (Izquierdo *et al.*, 2003). As of a few years ago, improved cultivars of quinoa have been tested as far north as Norway and Iceland. The further north, the shorter the growing season, due to later spring and earlier autumn, both imply lower temperatures.

In the United States of America, during the early 1980s, Colorado State University introduced quinoa at northern latitudes in Colorado, and a commercial production on 500 ha was soon achieved. Today, varieties adapted to the conditions in the centre of the United States of America, in the foothills of the Rocky Mountains, are cultivated on around 50 ha (personal communication). Most of the production takes place in the highlands of the San Luis Valley at an altitude of approximately 2 000 masl.

In Canada, a region similar in size to northern Europe, quinoa has been grown since the early 1990s, mainly in Saskatchewan. The current production level is around 800 ha (personal communication). In the vicinity of Canada, field tests have been initiated in the state of Washington, with the aim of introducing quinoa to the northern United States of America as a staple crop.

In 2009, the first large-scale, commercial quinoa production trial in Europe was carried out. It took place with a French asparagus company AbbottAgra (www.abbottagra.com), now also a quinoa company, in northwest France, in the department of Maine-et-Loire. Production was 140 tonnes of quinoa on 100 ha in 2009, 210 tonnes on 150 ha in 2010, and 270 tonnes on 250 ha in 2011. In both 2010 and 2011, the crop suffered from lack of spring rain. Yields reached up to 3 tonnes/ha, by using Dutch, sweet, relatively late-maturing cultivars.

The distribution of quinoa for research purposes and initiating commercial production in northern Europe is seen in Figure 1.

Figure 1. Distribution of quinoa in northern Europe (marked in red)

Breeding

Breeding of quinoa in new regions should concentrate on uniformity, early maturity, high yield and quality, as well as industrial uses of the seed and of specific ingredients. The ideal variety of quinoa for seed production in northern Europe is one which matures uniformly and early. A growing period of less than 150 days would normally be regarded as beneficial. Quinoa should also have a consistently high seed yield and it should be short and non-branching to facilitate mechanical harvesting (Figure 2). Saponin is a bitter compound present in varying amounts in the seed hull of most cultivars. Their function is a general defence against biotic stresses and for this reason they may be desirable in organic production. However, the presence of saponins requires that seeds be dehulled and washed before consumption – traditionally a labour-demanding process. In the case of commercial production with industrial processing techniques, saponin removal means increased costs. Size, shape and compactness of the inflorescence may be important for the rate of maturation. A large open inflorescence will dry more quickly after rain and morning dew than a small, compact one, but it may also be prone to seed loss, as quinoa is not very domesticated, and there are few modern varieties available. Fodder types should be tall, leafy and late maturing, with a

Figure 2: Two types of quinoa, branching and non-branching

high dry matter yield and preferably a low saponin content. Quinoa should be considered for cultivation in temperate climates, as it offers good potential in organic farming systems. Quinoa has been selected as a potential new protein crop for organic feed in Denmark. Field trials in Denmark have demonstrated seed yields of 2 tonnes/ha, with 12–16% protein content and 6–8% fat. There is wide variation in seed yield depending on year and location; this may be due to crop establishment or to weed control measures and harvest and post-harvest techniques, which still need to be optimized (Jacobsen *et al*., 2010).

In the Netherlands, breeding programmes led to the first European variety, 'Carmen', characterized by low stature, compact panicle and early maturation. Further research aimed to increase yield and reduce the saponin level (Limburg and Mastebroek, 1996; Mastebroek and Limburg, 1996; Mastebroek and Marvin, 1997). A second variety, 'Atlas' – the first sweet, saponin-free variety outside the Andes – was launched. At present, there are both Dutch and Danish varieties of quinoa registered in Europe (Naturerhverv, 2013) (Table 1).

Quinoa crop management in northern Europe

Jacobsen *et al*. (1994) found that quinoa cultivars selected for north European growing conditions were well adapted to sandy soils in Denmark, although a significant yield increase was experienced when the amount of nitrogen fertilizer was increased from 40 to 160 kg N/ha. Yield increased by 16%, 11% and 3% when the nitrogen supply was increased from 40 to 80, from 80 to 120 and from 120 to 160 kg N/ha, respectively. In southern Germany, quinoa cv. 'Faro' and 'Cochabamba' responded well to N fertilization, with a 94% yield increase at 120 kg N/ha (Schulte auf'm Erley *et al*., 2005). N fertilization was effectively utilized for quinoa seed production within the studied range up to 120 kg fertilizer N/ha. Estimated yield potential often exceeds the observed yields, indicating that even higher rates of nitrogen application may increase yield (Ørum *et al*., 2013).
Hoeing increases yield more than harrowing due to better weed control, but overall yield increase can be achieved by adopting either method. Regression analysis showed that crop yield is related to weed dry matter and showed no indications of higher crop damage associated with weed harrowing. Protein content is low when weeds are not treated, and increases significantly when weeds are controlled. In conclusion, inter-row hoeing is more efficient than weed harrowing in terms of weed control. Nevertheless, weed harrowing should be optimized in future trials in narrow row spacing systems, as results indicate that weed harrowing is an effective supplement to inter-row hoeing (Jacobsen *et al*., 2010).

A model expressing yield as a function of plant density shows the optimal plant density for high yield to be 327 ± 220 plants/m^2. This plant density is the top point of the curve relating yield to plant density. However, the large standard deviation indicates that similar yields may be obtained from a wide range of densities (Jacobsen *et al*., 1994).

The inheritance of some qualitative characters is known, including genetic and cytoplasmic male

Table 1: Registered European quinoa cultivars

Cultivar	Origin	Registration	Expiration	Breeder	Note
Carmen	Netherlands	16/6 1997	1/5 2022	PRI	
Atlas		16/11 1999	18/10 2024	PRI	Sweet
Pasto		16/2 2005	30/1 2030	PRI	Sweet
Riobamba		16/2 2005	30/1 2030	PRI	Sweet
Carina		Com		CPRO-DLO	
Dorado		Com		CPRO-DLO	
Serena		Com		PRI	
Puno	Denmark	1/1 2010	13/12 2034	Quinoa Quality	
Titicaca		1/1 2010	13/12 2034	Quinoa Quality	

Table 2: Development stages of quinoa (after Jacobsen and Stølen, 1993)

Stage	*Description*	*Stage*	*Description*	*Stage*	*Description*
0	**Vegetative phase**	8	**Anthesis**	14	**Seed set** 1/3 seed set
1	**Bud formation** Bud covered by leaf	9	Half flowering	15	Half seed set
2	Bud visible	10	Full flowering	16	2/3 seed set
3	Bud distinct			17	Full seed set
4	Bud ca. 0.5 cm	11	**Floral dehiscence** Onset	18	**Maturity** Leaves: Green > yellow
5	Bud ca. 1 cm	12	Most flowers dehisced	19	Yellow > green
6	Onset of pyramid shape	13	Only wilted anthers	20	Mature
7	Distinct pyramid shape			21	Wilted

sterility, and this may be valuable for future breeding (Jacobsen and Stølen, 1993). A developmental stage scale has also been defined (Table 2).

The Danish quinoa accession, 'Olav', has been demonstrated to have a base temperature (temperature at which germination is initiated) of 3°C, an optimum temperature of 30°–35°C, and a maximum temperature of 50°C. The thermal time requirement to germination, defined as root protrusion, is 30°Cd (Jacobsen and Bach, 1998). The base temperature of 3°C is in the normal range for temperate crops, while the optimum temperature is similar to that for tropical crops (Garcia-Huidobro *et al.*, 1982), indication that the Danish quinoa could germinate and establish satisfactorily in both temperate and tropical regions. The low thermal time for root protrusion (30°Cd) shows a quick response to temperature, which is beneficial in northern regions where the growing season is short.

A description of cultivation instructions for quinoa production under north European conditions is given in Plate 1, based on experiences from Denmark and other north European countries during the last 20 years of research.

General discussion

There is an increasing interest in quinoa in the global market. This is in part due to the extraordinary nutritional characteristics of quinoa. Its high nutritional quality makes it beneficial not only for vegetarians and vegans, but also for health-conscious people. Furthermore, quinoa is gluten free, which makes it favourable for people suffering from coeliac disease. Imports of quinoa by the European Union have increased rapidly in recent years. Particularly in France, the Netherlands and Germany, and more recently in the United Kingdom and Scandinavia, quinoa consumption has increased. Bolivia provides 94% of EU quinoa imports (CBI Market Information Database).

Quinoa is an alternative to stable, global food products, such as rice and wheat flour, and it is superior in terms of nutritional value and abiotic stress tolerance. Therefore, it is believed that the current trend will continue, which is why 2013 was nominated the International Year of Quinoa by FAO. The potential for cultivation of quinoa in Europe was previously estimated at 2 million ha (Galwey, 1993), but to substitute a mere 10% of rice with quinoa will require over 30 million ha more worldwide. The potential is huge, also in northern Europe, where for several years companies have been working with Bolivian quinoa to develop new products. Northern Europe has also demonstrated its ability to develop new kinds of cuisine, looking towards, for example, Nordic food.

Quinoa is destined to play an important role in the future of Nordic food preparation, in both high level gastronomy and simple everyday dishes.

Plate 1: Instructions for mechanized cultivation of quinoa in northern Europe

Establishment
The most critical period in the cultivation of quinoa in northern Europe, and elsewhere, is the initial establishment, which has to be quick and efficient. Quinoa is sensitive to suboptimal conditions at the time of sowing – deep sowing, heterogeneous seed bed, low soil temperature and especially poor seed quality – which all lead to yield reduction.

Seed bed
The seed bed must be optimal, fine textured and with sufficient humidity for quick germination and establishment of the plants. The seed bed should be free from weeds at sowing time. Weed problems are most severe at a late sowing.

Sowing conditions
Optimal sowing conditions are created by using high quality seeds with a high germination percentage and vitality, sowing at 1–2 cm depth in a uniform, fine-structured, humid seed bed, with a soil temperature above 0°C.

Sowing date
Early sowing after the winter and as soon as the frost has left the soil has given good results, if the first month of spring (April) is relatively dry. If the period after sowing is humid and cold, seedlings or plants with 2–4 leaves can be attacked by soil-borne diseases and pests, such as Fusarium sp.
Quinoa should be grown as a spring crop, as it cannot overwinter in the field.

Row spacing
Quinoa can be sown on 50, 25 or 12.5 cm. If quinoa is sown with a row spacing of 25–50 cm, hoeing can be applied. If a sowing is done at cereal distance (12.5 cm), weeds can only be controlled by harrowing.

Sowing rate
There is no correlation between plant density and yield, which shows the compensatory capability of quinoa. If there are few plants, they will be large and each have high yield. However, a

Sowing in an optimal seed bed

Emerged quinoa seedlings

relatively high density is preferred in order to secure uniform plants and maturity, therefore, 100 plants/m2 is recommended, obtained with a sowing rate of approximately 10 kg/ha.

Weeds
No herbicides controlling two-leaved weed species can be used in quinoa. For this reason, and given the interest in producing quinoa organically, the mechanical methods of hoeing, harrowing and flame treatment have been studied.

Flame treatment: As quinoa seems to emerge faster than any weed species, it is not possible to use flames to combat weeds before quinoa emergence.

Hoeing: For optimal weed control, it is important to sow in a clean seed bed, and allowing weeds

Harrowing

Hoeing

to germinate in a false seed bed can be very effective. Hoeing should take place as early as possible, but without covering the quinoa plants with soil between rows. In a subsequent control, it is possible to drive faster, creating a hilling which will have a positive effect on weed control in the row. Hoeing allows for accurate treatment between the rows, which makes it easier to control weeds, as it is possible to work deep in the soil and at high speed without damaging the quinoa. Crop soil cover should be avoided, although quinoa is relatively tolerant and may survive being covered.

Harrowing: This technique is easy to perform irrespective of how the crop was sown, and it can be done at high speed. The disadvantage is that the crop must be ahead of the weeds in order to avoid damage. It has, however, been demonstrated that quinoa can tolerate quite tough harrowing without damage to the crop.

Both weed control strategies result in loss of quinoa plants. Early hoeing may cause crop soil cover and result in loss of plants. Harrowing results in loss of the smallest plants as it is necessary to drive relatively fast for maximum weed control. Seed yield is highest with an efficient weed control strategy, and in general hoeing has given better results than harrowing. Prices for hoes and harrows are similar.

Manure

In an organic production system, nitrogen is normally applied to quinoa in the form of manure containing 80–120 kg N/ha. Quinoa may respond positively to higher levels.

Diseases and pests

Normally there are relatively few problems with diseases and pests in quinoa, although downy mildew (Peronospora variabilis) is seen every year everywhere quinoa is grown. This is especially the case under humid conditions with temperatures of 15°–20°C. The disease is less important if the summer is dry. Lack of disease control may result in significant yield decrease.

Harvest

Early harvest is essential in mountain regions and at high latitudes, requiring early establishment and growth in the spring. This enables the crop to avoid a cold, humid autumn climate in northern latitudes, which makes harvest more difficult, increases drying costs and reduces seed quality. At high altitudes, it is desirable to avoid drought and frost towards the end of the growing season. A late sowing or a cold growing season will delay development and harvest.

Harvest can be carried out with a combine harvester, putting the bridge close together, and reducing the air current. Yield is up to 2 tonnes/ha with properly adapted cultivars.

Good plant density in a clean crop

Quinoa close to maturity

Sowing dates, early and late

Commercial harvest

Seed yield

Harvested seed

Nutritional value

Quinoa has a high oil content (6% compared with 2% in cereals), and a high content of polyunsaturated fatty acids (omegas). It has a high protein content (14–18%), including a high lysine and methione content (double that of cereals). Quinoa has a high iron content (50% higher than in cereals), higher than any other crop.

Uses

Quinoa is attractive for food as well as animal feed. The main use of the primary product – the seed – is human consumption, and in South America the other plant parts are used for animals. Also in northern Europe, the main market is the food market. However, quinoa has a high feed value, as a result of the protein quality, starch content and high methionine composition, making it perfect for pig and chicken feed.

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