Height growth and flushing in common walnut (*Juglans regia* L.): 5-year results from provenance trials in Great Britain

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Summary

A collection of common walnut (*Juglans regia* L.) genotypes from the species’ natural and introduced ranges was assembled in 1997 to test their suitability for timber production in Britain. Field trials were established across three sites in southern England during winter 1998, containing 18 provenances. Tree height was measured annually, allowing height increment to be calculated and, during spring 2003, flushing (leaf-emergence) and frost injury were assessed. Survival was high with 98.7 per cent of trees alive after five growing seasons. At the end of the fifth growing season (2003) overall mean tree height was 138 cm but significantly different between sites (*P* ≤ 0.001) and provenances (*P* ≤ 0.001); provenance × site interaction also occurred (*P* ≤ 0.001). Overall growth was best at the Somerset site and worst at the Gloucestershire site. Height increment averaged 25 cm per year but varied significantly (*P* ≤ 0.001) between provenances, sites and for provenance × site interaction. The Turkish provenance T1 grew 285 per cent more in height in Somerset than in Gloucestershire. Progression of flushing was significantly different (*P* ≤ 0.001) for provenances at one site and a positive correlation (*P* ≤ 0.001; *r*² = 78 per cent) was identified between early flushing and frost injury. In the earliest flushing provenance (T2, Turkey), 55 per cent of trees were injured by late frosts during April and May 2003. Multi-trait ranking, based on vigour and late-flushing, indicated that provenances from more northerly latitudes, and from within the introduced range of the species, performed best after 5 years.

Introduction

Rationale

Common walnut (*Juglans regia* L.) is one of the ancient introductions to Britain but today there are probably fewer trees than at any time since the late sixteenth or early seventeenth centuries (Evelyn, 1678; Roach, 1985; Savill, 1991). Interest in walnut timber waned with the increasing availability of tropical hardwoods from the early nineteenth century onwards (e.g. Marshall, 1803).
and it has been infrequently planted since that time, particularly as a forest tree (Locke, 1987). There is also an increasing awareness by European consumers that the use of tropical timbers may contribute to deforestation, resulting in a reluctance to buy them. There are therefore good reasons to believe that valuable, decorative, temperate hardwoods are likely to be in much greater demand as tropical supplies decline.

*Juglans regia* is perhaps the finest of these valuable species, and is seen as a tree that could regain the place it had centuries ago, as the provider of high quality timber on relatively short rotations. The wood is used for making quality furniture and producing highly figured veneers, usually from burrs, which are used for cabinet-making and decorative panels (Berenyi *et al.*, 1990; Hart, 1991; Natale *et al.*, 1993).

To encourage a revival of interest in walnut, planting stock must be made available to landowners that is capable of producing straight-stemmed and finely branched trees, performing well in Britain’s climate. Phenotypes seen in Britain today are often of poor form for timber production because their likely origin is from continental European trees originally selected for nut production. Phenotypes for timber or nut production are generally viewed as incompatible because good phenotypes for timber (e.g. long straight stems and fine branches) have deliberately been selected against. Short-boled, spreading and branched trees were sought for high nut productivity and ease of harvesting. Additionally, some phenotypes in Britain may originate from ancient introductions, from environments unsuitable for widespread cultivation in the British climate, although positive adaptation to Britain would occur over generations.

*Previous walnut research*

*Juglans regia* is a species well known to be exacting in its site requirements (Steven, 1927; Chard, 1949; Evans, 1984; Istvan and Tibor, 1990; Savill, 1991). Steven (1927) suggested latitudinal limits of between 44° and 54° N for successful cultivation, which in Britain would limit cultivation to the south of England. The major problem with growing walnuts in Britain, and in fact throughout its natural and introduced ranges, is damage by frosts, both in late spring, when young shoots and flowers are very susceptible, and early autumn (Evans, 1984; Savill, 1991). The importance of selecting for late leaf flushing in breeding strategies for walnut cannot be overstated and potentially may be achievable, as flushing is a highly heritable trait ($h^2 = 0.96$; Hansche *et al.*, 1972).

Given the economic potential from producing home-grown walnut timber, and the difficulties associated with its cultivation, it is perhaps surprising that so little research has been conducted on developing better methods of silviculture or on testing improved material for timber production in Britain. Between 1986 and 1987, four experiments were established by the British Forestry Commission to assess the growth and survival of two provenances of *J. regia* (Hungarian and English) and six of *J. nigra* L. (Kerr, 1993). Four sites were used in the south of England, the most northerly being situated in Northamptonshire. The conclusions of this study were that the site was of greater importance than provenance in terms of survival and height increment, and that on the range of sites tested, *J. nigra* performed better than *J. regia*. However, a very limited range of material was tested.

Provenance collections of *J. regia* were initiated in the early 1980s in Switzerland and included 20 sources from wild populations in India, Pakistan, Nepal and Bhutan (Rotach, 1998). Between 1997 and 2000, a European Commission-funded joint research programme (FAIR-CT96-1887) (W-BRAINS: Walnut – Basic Research for Agroforestry and Industry: Network and Standards) focused on the production of high quality wood from walnut species, although there was no UK participation within this programme.

*Aims and objectives*

A range-wide collection of *J. regia* material was gathered during the autumn of 1997 to facilitate two main aims; firstly, selecting new and improved walnut phenotypes for timber production in the UK, and secondly, analysing genetic variation in the species. Field trials were established to test the performance of a wide-ranging sample of *J. regia* genotypes in environmental conditions typical of suitable forestry sites in southern England, and to assess their suitability for producing quality hardwood timber. Most of this genetic material
is being tested in Britain for the first time and these trials provide a unique opportunity for the long-term assessment of the species’ future potential as an economic crop.

Materials and methods

Provenance trials

Material

*Juglans regia* genotypes were sampled from within the natural and current European ranges of the species. Two approaches were taken in gathering material. Firstly, scientists and tree breeders within national forest institutes and similar organizations were approached and asked whether seeds could be supplied for research. Secondly, a seed collecting expedition to Kyrgyzstan, within the natural range of *J. regia*, was undertaken in 1997 (Hemery, 1998).

In provenance selection, the movement of plant material from sources of origin that differ geographically or environmentally from those at the introduced location can be problematic, particularly if high altitude or high latitude sources are moved to low altitudes or low latitudes (Zobel and Talbert, 1984). However, high altitude sources from low latitudes can often be introduced successfully to low altitude locations at high latitudes (Burley, 1976; Zobel and Talbert, 1984). The mountainous Central Asian country of Kyrgyzstan is situated at the northern limit of the species’ natural range (Schmucker, 1942; McGranahan and Leslie, 1991; Figure 1). Seed collections were therefore centred on two areas in Kyrgyzstan, the Chatkal and Fergana mountain ranges, from origins averaging 1617 m and 1380 m a.s.l., respectively (Hemery, 1998).

Sampling in Kyrgyzstan targeted 20–30 parent trees per provenance with a minimum of 50 m between individuals, following FAO (Food and Agriculture Organization of the United Nations) (1995) guidelines. For the seed collections from other countries, where there was less control over the collection method, some broad prescriptions were outlined to collectors; namely to provide environmental data and tree location information, and to collect seed from 30 individual trees and 10 seeds per tree, maintaining mother tree identity where possible.

Field trial design

Overall, material from 25 provenances, including 371 half-sib progeny, was planted in three field trials during the autumn of 1998 (Hemery, 2000) (Table 1). However, only 18 provenances are replicated across all three trial sites. The seven remaining provenances are bulked, without

![Figure 1. The natural range of walnut *Juglans regia* (shown in dark grey), based on Schmucker (1942) and McGranahan and Leslie (1991). The position of the 18 provenances is indicated by a solid circle, in which E = Spain, J = Tajikistan, K = Kyrgyzstan, P = Iran, R = Romania, S = Slovakia and T = Turkey.](https://academic.oup.com/forestry/article-abstract/78/2/121/544762)
progeny information, and present only at the two smaller field trials (Gloucestershire and Somerset). The bulked provenances consisted of low numbers of trees and were not assessed for this paper, nor are the progeny level data.

The trial design was complex, as the trials had to provide material both for genetic analysis as well as being an ex situ collection to provide material for future breeding programmes (Hemery, 2000). As much material as possible needed to be included and maintained in the field trials. Low numbers of plants were therefore included for some provenances and progeny, leading to an imbalance of numbers within and between provenances.

The provenance trials were in randomized complete block designs incorporating non-contiguous multiple-tree plots, meaning that within any block there were between one and 10 (mean of five) individuals representing a provenance, and whose positions were assigned at random within the 100-tree blocks, distributed across three sites in southern England (Table 2). The number of blocks within a site varied between 14 in Oxfordshire and four each in Gloucestershire and Somerset (22 in total). Progeny were not equally represented at all sites, therefore a provenance was usually represented by a different combination of progeny at each site. Progeny were distributed across all three sites wherever possible.

Three trial sites were selected for planting to permit the assessment of genotype × environment interaction. The sites differ widely in altitude, shelter and soil type and therefore provide contrasting test conditions (Table 2). Soil pH at all sites was within the recommended range for walnut silviculture, pH 6.0–7.5 (Evans, 1984; Becquey, 1997).

The trees on all field trial sites were planted during November and December 1998 and protected with 0.75-m treeshelters, to prevent damage from browsing animals and herbicide spray drift and promote good establishment (Hemery and Savill, 2001). Wide spacings were used (Table 2), although more closely spaced than traditionally recommended for walnut (10–15 m; Evans, 1984; Becquey, 1997), with the expectation that canopies would not close for 15–20 years (Hemery, 2000).

Assessments and data analyses

Tree heights were measured annually to the nearest centimetre using a measuring rule. When first

<table>
<thead>
<tr>
<th>Provenance</th>
<th>Name</th>
<th>Country of origin</th>
<th>Latitude (° N)</th>
<th>Longitude (° E)</th>
<th>Altitude (m a.s.l.)</th>
<th>No. of progeny</th>
<th>No. of trees in trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>Ak-Terek</td>
<td>Kyrgyzstan</td>
<td>41.25</td>
<td>72.75</td>
<td>1700</td>
<td>11</td>
<td>23</td>
</tr>
<tr>
<td>K2</td>
<td>Ak-Terek</td>
<td>Kyrgyzstan</td>
<td>41.25</td>
<td>72.75</td>
<td>1390</td>
<td>17</td>
<td>95</td>
</tr>
<tr>
<td>K3</td>
<td>Ak-Terek</td>
<td>Kyrgyzstan</td>
<td>41.25</td>
<td>72.75</td>
<td>1860</td>
<td>26</td>
<td>152</td>
</tr>
<tr>
<td>K4</td>
<td>Sharap</td>
<td>Kyrgyzstan</td>
<td>41.25</td>
<td>72.75</td>
<td>1620</td>
<td>26</td>
<td>161</td>
</tr>
<tr>
<td>K5</td>
<td>Yaradar</td>
<td>Kyrgyzstan</td>
<td>41.25</td>
<td>73.00</td>
<td>1260</td>
<td>20</td>
<td>140</td>
</tr>
<tr>
<td>K6</td>
<td>Shaidan</td>
<td>Kyrgyzstan</td>
<td>41.25</td>
<td>72.75</td>
<td>1590</td>
<td>26</td>
<td>184</td>
</tr>
<tr>
<td>K7</td>
<td>Kyzyl-Ungur</td>
<td>Kyrgyzstan</td>
<td>41.40</td>
<td>73.00</td>
<td>1400</td>
<td>17</td>
<td>151</td>
</tr>
<tr>
<td>K8</td>
<td>Katar-Yangak</td>
<td>Kyrgyzstan</td>
<td>41.25</td>
<td>72.75</td>
<td>1900</td>
<td>24</td>
<td>167</td>
</tr>
<tr>
<td>K9</td>
<td>Kyok-Sarau</td>
<td>Kyrgyzstan</td>
<td>41.25</td>
<td>72.75</td>
<td>1830</td>
<td>26</td>
<td>190</td>
</tr>
<tr>
<td>K10</td>
<td>Kyr-Sai</td>
<td>Kyrgyzstan</td>
<td>41.75</td>
<td>72.00</td>
<td>1320</td>
<td>27</td>
<td>208</td>
</tr>
<tr>
<td>K11</td>
<td>Ters-Kolt</td>
<td>Kyrgyzstan</td>
<td>41.75</td>
<td>72.00</td>
<td>1440</td>
<td>27</td>
<td>191</td>
</tr>
<tr>
<td>E1</td>
<td>Catalonia</td>
<td>Spain</td>
<td>42.00</td>
<td>3.00</td>
<td>175</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>J1*</td>
<td>Tadzikistan</td>
<td>Tadzikistan</td>
<td>38.95</td>
<td>70.00</td>
<td>*</td>
<td>7</td>
<td>60</td>
</tr>
<tr>
<td>P1*</td>
<td>Karaj</td>
<td>Iran</td>
<td>36.28</td>
<td>52.00</td>
<td>*</td>
<td>5</td>
<td>38</td>
</tr>
<tr>
<td>R1</td>
<td>Romania</td>
<td>Romania</td>
<td>45.84</td>
<td>25.90</td>
<td>478</td>
<td>27</td>
<td>63</td>
</tr>
<tr>
<td>S1</td>
<td>Slovakia</td>
<td>Slovakia</td>
<td>48.24</td>
<td>18.96</td>
<td>215</td>
<td>34</td>
<td>107</td>
</tr>
<tr>
<td>T1</td>
<td>Trabzon</td>
<td>Turkey</td>
<td>39.98</td>
<td>40.00</td>
<td>776</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>T2</td>
<td>Anatolia</td>
<td>Turkey</td>
<td>38.70</td>
<td>42.45</td>
<td>1650</td>
<td>21</td>
<td>38</td>
</tr>
</tbody>
</table>

* Provenances from seed orchards collections in France; Institut National de la Recherche Agronomique (INRA).
Table 2: Summary of field site environment and trial design

<table>
<thead>
<tr>
<th>Trial site</th>
<th>Oxfordshire</th>
<th>Gloucestershire</th>
<th>Somerset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site environment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latitude/longitude</td>
<td>51° 38' N/1° 12' W</td>
<td>52° 2' N/1° 47' W</td>
<td>51° 3' N/3° 0' W</td>
</tr>
<tr>
<td>Altitude (m a.s.l.)</td>
<td>50</td>
<td>245</td>
<td>15</td>
</tr>
<tr>
<td>Aspect</td>
<td>Flat</td>
<td>SSE</td>
<td>Flat</td>
</tr>
<tr>
<td>Slope</td>
<td>Flat</td>
<td>Hill top/gentle slope</td>
<td>Flat</td>
</tr>
<tr>
<td>Soil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>7.6</td>
<td>8.0</td>
<td>7.3</td>
</tr>
<tr>
<td>N (mg l(^{-1}))</td>
<td>4</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>P (mg l(^{-1}))</td>
<td>19</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>K (mg l(^{-1}))</td>
<td>153</td>
<td>107</td>
<td>120</td>
</tr>
<tr>
<td>Mg (mg l(^{-1}))</td>
<td>115</td>
<td>25</td>
<td>78</td>
</tr>
<tr>
<td>Texture</td>
<td>Sandy clay loam</td>
<td>Sandy silt loam</td>
<td>Sandy clay loam</td>
</tr>
<tr>
<td>Geology(^*)</td>
<td>Valley gravel</td>
<td>Inferior Oolite</td>
<td>Upper (Keuper) Marls</td>
</tr>
<tr>
<td>Previous use of site</td>
<td>Arable</td>
<td>Arable</td>
<td>Grass pasture (at least 10 years)</td>
</tr>
<tr>
<td>Site preparation</td>
<td>Ploughed/cultivated/sown with grass</td>
<td>Ploughed/cultivated</td>
<td>None</td>
</tr>
<tr>
<td>Trial design</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data level</td>
<td>Combined provenance/progeny</td>
<td>Provenance only</td>
<td>Provenance only</td>
</tr>
<tr>
<td>No. of blocks (reps)</td>
<td>14</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>No. of trees</td>
<td>1400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Spacing (metres)</td>
<td>5 \times 5</td>
<td>4 \times 4</td>
<td>3.8 \times 3.8</td>
</tr>
<tr>
<td>Protection</td>
<td>0.75 m shelters</td>
<td>0.75 m shelters</td>
<td>0.75 m shelters</td>
</tr>
</tbody>
</table>


Figure 2. Scoring system adopted for assessing flushing in the walnut provenance trials. Flushing was scored for terminal buds only, although scores 1 and 3 are illustrated on lateral buds. Scores 5 and 6 (not shown) represented shoot expansion of <4 cm and >4 cm, respectively.

planted, stem diameter was measured at the root collar to the nearest millimetre using callipers. Initial height and stem diameter were used as co-variates in assessment of growth and survival, particularly in attempting to account for maternal effects and non-genetic variation (Burdon and Sweet, 1976). Statistical assessments for height and height increment were based on plot means,
Table 3: (a) Flushing scores used to assess leaf emergence and injury scores recorded (b) on 15 April, and (c) on 23 May 2003

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Bud closed</td>
</tr>
<tr>
<td>1</td>
<td>Bud breaking – scales separating</td>
</tr>
<tr>
<td>2</td>
<td>Bud breaking: leaves visible</td>
</tr>
<tr>
<td>3</td>
<td>Leaves emerging: &lt;2 cm long</td>
</tr>
<tr>
<td>4</td>
<td>Leaves emerging: &gt;2 cm long</td>
</tr>
<tr>
<td>5</td>
<td>Shoot expanding: &lt;4 cm growth</td>
</tr>
<tr>
<td>6</td>
<td>Shoot expanding: &gt;4 cm growth</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable assessed at end of 2003</th>
<th>Oxfordshire (n = 52)</th>
<th>Gloucestershire (n = 72)</th>
<th>Somerset (n = 72)</th>
<th>All sites (n = 396)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survival %</td>
<td>98.5</td>
<td>99.6</td>
<td>98.4</td>
<td>98.7</td>
</tr>
<tr>
<td>No. dead</td>
<td>27</td>
<td>2</td>
<td>5</td>
<td>34</td>
</tr>
<tr>
<td>Height (cm) Mean</td>
<td>136.4</td>
<td>109.4</td>
<td>172.7</td>
<td>138.1</td>
</tr>
<tr>
<td>SE</td>
<td>1.6</td>
<td>1.3</td>
<td>4.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Height increment Mean</td>
<td>124.2</td>
<td>97.7</td>
<td>159.5</td>
<td>125.8</td>
</tr>
<tr>
<td>SE</td>
<td>1.5</td>
<td>1.1</td>
<td>4.4</td>
<td>1.6</td>
</tr>
</tbody>
</table>
regression; $y = -0.396 + 0.557x$, where $y$ was the frost injury score and $x$ the flushing score.

## Results

### Tree growth

### Survival

Survival across the three provenance trial sites was high overall at 98.7 per cent at the end of five growing seasons (Table 4). With one exception, a single tree within provenance T2 (Anatolia, Turkey), mortality was confined to the Kyrgyz provenances. There was no significant variation for mortality between provenances, blocks or sites. Root collar diameter at planting was significant ($P = 0.006$) when included as a covariate in the analysis of variance model. This indicates the importance of initial seedling size in relation to obtaining good tree survival. The mean diameter of dead trees was 6.6 mm (SE = 0.6), compared with a mean of 10.1 mm (SE = 0.1) for those which survived.

### Height increment

Mean tree height increment was 126 cm over the five years assessed, averaging 25.2 cm per year (Table 4). Variations in tree height increment between 1998 and 2003 were highly significant ($P \leq 0.001$) for all factors in the model of analysis, including between sites (Table 5).

There was significant ($P \leq 0.001$) provenance × site interaction for height increment, which is clearly evident when height increment is ranked by provenance within each site (Table 6). Provenance T1 (Turkey, Trabzon region, 776 m a.s.l.)

### Table 5: Analysis of variance results for tree height increment in 2003 for the 18 provenances across three sites, using plot means

<table>
<thead>
<tr>
<th></th>
<th>d.f.</th>
<th>Mean sq.</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>2</td>
<td>73244.2</td>
<td>206.32</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Block-within-site</td>
<td>19</td>
<td>1134.4</td>
<td>3.2</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Provenance</td>
<td>17</td>
<td>6004.2</td>
<td>16.91</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Provenance × site</td>
<td>34</td>
<td>1341.4</td>
<td>3.78</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Residual (error)</td>
<td>322</td>
<td>355</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The least significant difference of means at 5% was 24.3 cm.

### Table 6: Mean 5-year (1998–2003) provenance height increments (cm) ranked within each trial site, based on multiple-tree plot means within $n$ blocks

<table>
<thead>
<tr>
<th>Provenance</th>
<th>Mean height increment (cm)</th>
<th>Provenance</th>
<th>Mean height increment (cm)</th>
<th>Provenance</th>
<th>Mean height increment (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxfordshire ($n = 14$)</td>
<td>Gloucestershire ($n = 4$)</td>
<td>Somerset ($n = 4$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1</td>
<td>162.7</td>
<td>R1</td>
<td>114.6</td>
<td>T1</td>
<td>242.4</td>
</tr>
<tr>
<td>R1</td>
<td>150.4</td>
<td>J1</td>
<td>112.7</td>
<td>J1</td>
<td>205.1</td>
</tr>
<tr>
<td>S1</td>
<td>148.5</td>
<td>S1</td>
<td>104.5</td>
<td>R1</td>
<td>192.4</td>
</tr>
<tr>
<td>P1</td>
<td>137.5</td>
<td>K5</td>
<td>101.0</td>
<td>P1</td>
<td>181.9</td>
</tr>
<tr>
<td>E1</td>
<td>129.7</td>
<td>K7</td>
<td>100.8</td>
<td>E1</td>
<td>178.1</td>
</tr>
<tr>
<td>K1</td>
<td>129.3</td>
<td>K9</td>
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The least significant difference of means at 5% was 24.3 cm.
Figure 3. Mean 5-year (1998–2003) tree height increments (cm) for provenances in relation to (a) latitude and altitude and (b) longitude and altitude of origin at the Oxfordshire trial site (location of field trial indicated by squares).

Figure 4. Fitted model based on a multiple regression for mean tree height increment (cm) within provenances at three field trials sites plotted against altitude of provenance source. Altitude (metres above sea level) of field trial sites: Gloucestershire 245, Oxfordshire 55 and Somerset 15.

provenance T1 grew least in height at the Gloucestershire site (245 m a.s.l.) growing only 85 cm. Other provenances performed more consistently, such as J1 and R1, both of which were within the top three ranking provenances for height growth at each site.

Relationship between origin and height increment
There were significant linear relationships ($P \leq 0.05$) for height increment against altitude, latitude and longitude of origin, although the percentage variation ($r^2$) was variable for longitude (48 per cent), altitude (47 per cent) and latitude (62 per cent). The relationship between both latitude and longitude with altitude is most clearly presented in three-dimensional plots (Figure 3). A broad clinal pattern is evident for reduced tree height increment with increasing distance of origin from the planting location.

The effect of altitude of origin on tree height increment was highly significant ($P \leq 0.001$) overall and between all three sites. The fitted model (Figure 4) illustrates the effect of altitude of origin on growth within and between sites, with the fitted model accounting for 76.8 per cent of the variance ($r^2$). The effect of altitude of origin on height increment was non-significant for Gloucestershire, but significant for Oxfordshire ($P = 0.024$) and Somerset ($P \leq 0.001$). Exploration of the altitudinal effect for Kyrgyz provenances only, where latitudes and longitudes of origin varied very little, revealed no significant variation of height increment within any field trial site.
CLOSED BUDS. Similarly, on the same day for provenance T2, where the mean was 1.95 (i.e. most of the leaves were visible; Figure 2), buds remained fully closed (score 0) in 10 per cent of T2 trees.

Tukey's HSD test revealed five homogeneous subsets for time of flushing (Table 7). Subsets 1 and 5 included no provenances in common. Of the late-flushing provenances, S1 (Slovakia) came from the most northerly origin (48.2° N), whilst the mother trees of provenances J1 and P1 were from Tajikistan and Iran, respectively.

Frost injury on 15 April 2003 (DAY 105)
No injury was recorded in provenances P1 (Iran) and S1 (Slovakia), mean flushing DAY 101 and DAY 103, respectively, during the frost period in

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Significance (P) 0.080 0.440 0.368 0.069 0.139

DAY 94 = 4 April 2003 and DAY 106 = 16 April 2003.
Provenances within any subset do not differ significantly from each other at P = 0.05.
n = number of trees sampled.
* Uses harmonic mean sample size = 40.631. The group sizes are unequal. The harmonic mean of the group sizes is used. Type 1 error levels are not guaranteed. Alpha = 0.05.

Flushing and frost damage
The three phenological traits studied (Table 3) at the Oxfordshire site all varied significantly (P ≤ 0.001) for provenances and blocks.

Flushing
Provenance T2 (Turkey) was the earliest to flush (DAY 94), followed by provenance S1 (Slovakia) (DAY 103), whilst provenance J1 (Tajikistan) was the latest to flush (on DAY 106). The average difference in development on any day between the earliest and latest provenances to flush was about four points on the flushing scale (Figure 2 and Table 3), which in the early stages of flushing amounted to an approximate difference of 18 days, and in the later stages, about 5 days.

There was also considerable variability in the flushing scores within any provenance. For example, on the 23 April (DAY 113), when the mean flushing score of provenance J1 was 1.15, 38 per cent of J1 trees still had completely closed buds. Similarly, on the same day for provenance T2, where the mean was 1.95 (i.e. most of the leaves were visible; Figure 2), buds remained fully closed (score 0) in 10 per cent of T2 trees.

Tukey's HSD test revealed five homogeneous subsets for time of flushing (Table 7). Subset 5 was made up of the three latest flushing provenances (P1 (Iran), S1 (Slovakia) and J1 (Tajikistan)) and subset 1, the 14 earliest. Subsets 1 and 5 included no provenances in common. Of the late-flushing provenances, S1 (Slovakia) came from the most northerly origin (48.2° N), whilst the mother trees of provenances J1 and P1 were from Tajikistan and Iran, respectively.

Frost injury on 15 April 2003 (DAY 105)
No injury was recorded in provenances P1 (Iran) and S1 (Slovakia), mean flushing DAY 101 and DAY 103, respectively, during the frost period in
The two extremes, S1 (least damaged) and T2 (most damaged), were represented only in the first and fourth subsets, respectively. The relationship between injury and flushing stage was much weaker for the May frost ($r^2 = 0.18$). On Day 143, when all of the provenances had flushed (mean score 5.2), the mean injury score for all provenances was 1.4, indicating that <40 per cent of leaves in the canopy were damaged by frost.

**Discussion and conclusions**

Given the wide range of material sampled, survival and early growth have been impressive by any standard. Results at this early stage in the life of the field trials already indicate a significant relationship between height increment and origin, which may become more significant in time. Morgenstern (1996) cites many such examples, demonstrating geographic clines for both flushing and growth. The variable response of provenances at the three British field trials, demonstrated here to be correlated with their source altitude, indicates that sources sampled from compatible environments perform best on a very good site (Somerset). However, on more marginal sites (Gloucestershire), even sources from higher elevations do not perform well.

It is clear that performance of the Kyrgyz provenances, for all assessed traits, was poor in comparison to other provenances in this study. The relative performance of all provenances, at one site (Oxfordshire), is illustrated in Table 8, where these are ranked for the desirable traits of vigour (height increment) and late-flushing. The overall ranking clearly demonstrates that three of the top five ranking provenances, E1, R1 and S1, were all sampled from regions within the introduced range of the species and from latitudes higher than 42° N (Table 1). The two other top ranking provenances (J1 and P1) were both sampled from seed orchards within existing European collections (Table 1). All these provenances seem more suited to the British climate having some local adaptation, therefore out-performing those from more southerly origins. These results compare well with a European-wide study of walnut where southern seed sources were the first to flush and most damaged by late spring frosts (Fady et al., 2001).
Similar results have been found with provenances of other species such as *Picea sitchensis* (Bong.) Carr. and *Pinus strobus* L., where those from colder, more northern regions flushed later than provenances from more southerly regions of North America (Burley, 1976; Li *et al.*, 1997).

The two Turkish provenances (T1 and T2) were amongst the lowest ranking provenances for flushing (Table 8). Provenance T2 originated from the second lowest latitude (Table 1). It was the earliest to flush and most badly damaged during both periods of frost. Atefi (2001) similarly found that walnuts from lower latitudes (Iran) flushed earlier than those from higher latitudes (France and USA). At present there is no evidence, based on geographic origin (Table 1), to explain why the best overall ranking (for both vigour and late-flushing) Kyrgyz provenances, K9, K5 and K1 (Table 7) performed better than other Kyrgyz provenances.

The apparent consistency of rank for provenances between vigour and late flushing presented

![Figure 6. Regression for vigour (increment of height) and flushing at the Oxfordshire trial site.](https://academic.oup.com/forestry/article-abstract/78/2/121/544762)

### Table 8: Summary of desirable phenotypic characters for provenances 5 years after planting at the Oxfordshire field trial

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Rank order: lower numbers are more desirable; higher numbers are less desirable.

Vigour was based on mean increment of height, and late flushing based on the mean date of flushing in Julian days recorded in 2003.

Overall rank is the total of the rank scores for each trait.
in Table 8 was explored by computing a linear regression for height increment and flushing (Figure 6) and the regression was highly significant ($P \leq 0.001$). This indicates that, despite starting growth earlier in the season, early-flushing provenances actually grew least in height compared with late-flushing ones. Frost injury is the cause, where damage to early growth necessitates reinitiation of growth from dormant buds. Subsequently, it may be hypothesized, the form of such trees may also be less desirable because trees with damaged terminal buds develop multiple leaders. In some species, e.g. Douglas fir ($Pseudosuga menziesii$ (Mirb.) Franco), strong negative correlations have been found between the time of leaf flushing and cold hardiness (Li and Adams, 1993; Aitkins and Adams, 1997). In these walnut provenance trials, there was an equally strong relationship (Figure 6). Other studies provide some evidence for a link between spring temperatures and forking (e.g. Day and Peace, 1946). A programme of form assessment in the field trials is planned from 2004 and these data will be important for multi-trait selection within the tree breeding programme.

Future research with the walnut trials will also include assessments at progeny level, allowing heritabilities to be calculated for selected traits, including late-flushing, form and vigour. A preliminary study of genetic diversity of the sampled genotypes using isozymes was inconclusive (Hemery, 2000), therefore it is hoped that, in the future, such work may be completed with a view to estimating the genetic structure of the sampled populations.

Acknowledgements

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