The Importance of Soil Fumigation:

Pacific Northwest Potatoes
Introduction

With a total value of production of nearly $4 billion in 2012, potatoes are the most valuable vegetable produced in the U.S. [1]. The primary use of potatoes in the U.S. is for processing (66% of potatoes sold), followed by table stock (28%), seed (6%) and livestock feed (1%) [2]. US consumption of potatoes was 122.4 lbs per capita in 2012, the highest of any vegetable [1].

The U.S. is the world’s fifth largest potato producer, after China, India, Russian Federation, and the Ukraine, accounting for 5% of global production in 2011 [3]. The U.S. exported $1.6 billion worth of potatoes in 2012 [1]. Japan is the largest US export market for potatoes, accounting for 25% of total export value, followed by Canada (21%) and Mexico (11%). Canada accounts for largest share of potato imports, with 81% of the total US import value of $1.1 billion [1].

Historically, Maine, New York and Pennsylvania were the main potato-producing states in the U.S. However, with westward expansion in the late 19th century, development of irrigation systems and refrigerated rail transport, Idaho, Washington and Colorado become dominant in US potato production. Significant advances in potato yields in the first half of the 20th century were attributed to improved potato varieties such as Russet Burbank, increased use of chemical fertilizers and pesticides, irrigation, increased grower specialization, improved cultural techniques and the shift in production to western states with higher concentrations of nutrient-rich volcanic soils that are optimal for potato production [4] [5]. Over the past few decades, the potato industry has consolidated considerably, which is believed to be due to large capital investments in equipment and storage facilities [4]. For example, in Idaho, the total potato acreage harvested declined only slightly between 1978 and 2007, from 364,243 acres in 1978 to 350,905 acres in 2007 [6][7]. In the same period of time, the total number of farms declined dramatically from 2,296 in 1978 to 703 in 2007 [6][7].

Idaho and Washington currently dominate US potato production, together accounting for over 50% of total production and 43% of total value of production in 2012 [2]. Other major potato producing states include Wisconsin, which accounted for 6% of total production, followed by North Dakota, Colorado and Oregon, each accounting for 5% of total production in 2012 [2].

Production Areas

Idaho is consistently ranked first in potato production and acreage in the U.S. The majority of potato production is adjacent to the Snake River Plain in southern Idaho where water is available for irrigation. Major production regions in Idaho, in order of importance, are: southeastern Idaho, eastern Idaho, the Magic Valley in south central Idaho and the Treasure Valley in southwestern Idaho. Washington State is consistently ranked second in potato production and acreage in the U.S. Potatoes are primarily produced in the eastern part of the state in the Columbia Basin and along the Snake River. A small portion of Washington State’s potato crop is produced on the west side of the Cascade Mountains. Oregon is among the leading potato producing states. The vast majority of potato acreage in Oregon is east of the Cascade Mountains, in the Columbia and Klamath River basins and the Treasure Valley. A small amount of production takes place west of the mountains [8].
Cultural Practices

The pre-plant period for any field includes all production seasons since the previous potato crop and the late fall, winter, and early spring just prior to the planting of the potato crop. The rotation of potatoes with other crops is an integral part of the pre-plant pest management strategy. Rotation to different crops in between potato plantings provides pest control benefits, loosens compacted soil when rotating from cereals with fibrous root systems, adds nitrogen when rotation from a legume crops such as alfalfa or beans, incorporates organic matter when rotating from crops such as small grains and corn, and carries nutrients over when rotations from vegetable or other high-input crops. Although pest management drives many crop rotation decisions, growers also consider crop economics, market forces and availability, and machinery when making final decisions about the crops they include in their rotation. Typical crop rotations vary across production areas, lasting from 2 to as many as 7 years [8].

Irrigation late summer to early fall can help to germinate volunteer weed seeds. It also helps growers get a good sample for nematode analysis, as increased moisture in the soil increases nematode egg hatch [8].

Fall bedding occurs after involves marking and hilling a field where potatoes will be grown the next spring to create beds. Primary tillage incorporates residue from the previous crop, reduces wheel traffic compaction from the previous season, improves water filtration and soil aeration, controls weeds and nematodes, loosens the soil for root penetration, and provides a suitable seedbed. Fall bedding is not practiced in the Columbia Basin [8].

Soil fumigation is mostly commonly performed in the fall to control nematodes, diseases such as Verticillium wilt, and sometimes weeds. Fumigation is scheduled to take advantage of optimum soil temperatures, to target the most susceptible stage of pests, to increase exposure time of nematicides, and to avoid the persistence of damaging fumigant residues at planting. Fall fumigation, in contrast to spring fumigation, allows for timely planting of the spring crop. Spring fumigation must wait for sufficiently warm soil temperatures, thereby postponing planting. For long-season cultivars, fall fumigation is a necessity. Ninety percent of the potato acres in Washington are fumigated, 82% of the potato acres in Oregon are fumigated, and 50% of the Idaho potato acres are fumigated [8]. Typically in this region, metam sodium is applied before planting at an application rate of 190 kg AI/ha. Sprinkler-head center pivot chemigation and tractor-drawn soil-incorporated shallow shank injection are the principal application methods used in applying metam sodium [9].

Sprinkler irrigation is used on more than 99% of the crop in Idaho. Sprinkler irrigation is used on approximately 90% of potatoes grown in the Columbia Basin, furrow and drip irrigation are used on the remainder. Seventy percent of Oregon's potato acreage is under center pivot irrigation systems. The remaining acres are irrigated by rill, wheel line, furrow, lateral move, and solid set systems [8].

Major Target Pests
Pre-plant soil fumigation is used in Pacific Northwest potato production to control a range of soilborne fungal diseases, nematodes and weeds.

Verticillium Wilt

Verticillium wilt is a major economic disease of potato wherever the crop is commercially grown. The disease is caused by either *Verticillium dahlia* or *Verticillium albo-atrum*, soilborne fungi that invade xylem elements, disrupt water transport in plants and cause vascular wilt in a variety of hosts. *Verticillium dahlia* infects a wide range of annuals and perennials and survives for relatively long period in soil as microsclerotia. *Verticillium albo-atrum* has a more limited host range, does not form microsclerotia and survives for relatively shorter durations in soil. Verticillium wilt is the major component of potato early-dying complex, which refers to the early senescence and death of a potato crop. Although infection may occur early in the growing season, symptoms generally do not develop until later in the season during rapid tuber bulking. Synergistic interactions of *V. dahlia* and *P. penetrans* (root lesion nematode) have been shown to occur in potatoes with some strains of *V. dahlia*, and may cause significant yield losses at population densities of each pathogen that would alone have little or no effect on the crop [10]. Verticillium wilt is endemic in many potato production areas of the United States, particularly in the Midwest and Pacific Northwest. In fields with a long history of potato production, it is a consistent yield constraint that requires intensive management. On land new to potato production, it may be absent in the first few years the crop is grown, but it almost invariably develops over time, requiring implementation of control measures to maintain high yields. In North America, yield reduction in moderately diseased fields can easily be 10-15% and in severely diseased field it can be as high as 30 to 50% [16].

Nematodes

Nematodes are one of the major limiting factors for potato production in the Pacific Northwest. Nematode infestation results in yield decline and reduction in quality. Predominant nematode pests are root-knot nematodes (*Meloidogyne* spp.), root lesion nematodes (*Pratylenchus* spp.) and stubby root nematodes (*Trichodorus* and *Paratrichodorus* spp.).

Columbia root-knot nematode and the northern root-knot nematode have been recognized as major nematode pests on potato and found in abundance especially in sandy soils [8][11][12]. The Columbia root-knot nematode is an important pest in the Columbia Basin and is present in most of the potato growing areas west of the Mississippi [13]. Columbia root-knot nematode is more problematic in Washington and Oregon, where the growing season is longer and there is more irrigation. Pressure is generally lower in Idaho [27]. Females feeding in the tubers and the development of live young cause enlargement or bumps in the outer layers of the tubers, rendering them useless for either fresh packing or processing. The nematodes have a wide host range leading to population increases when other susceptible crops are grown in rotation with potatoes. Damage is usually most severe following alfalfa hay crops and during years with high spring temperatures. They cause field damage that is localized, usually in patches of various sizes, or may be spread throughout an entire field and plants become chlorotic and stunted. Damaged roots are not able to obtain soil nutrients and above ground symptoms appear as nitrogen or micronutrient deficiencies. Plants may wilt easily, especially in warm weather, due to root damage even though soil moisture may be adequate [11][12]. Infestation can render tubers unmarketable. When the level of infected tubers exceeds 5%, processors and packers generally reject all potatoes from that field. Generally, Columbia root-knot nematodes cause more damage to potatoes...
than do northern root-knot nematodes. Therefore, any detectible level of Columbia root-knot nematode warrants pesticide treatment [8]. In addition, some export markets, in Southeast Asia, Mexico and other countries, have a zero tolerance for Columbia root-knot nematode [19].

The root lesion nematode (*Pratylenchus* spp.), a migratory endoparasite on potatoes, is a concern to potato growers because it reduces yield by indirectly weakening the plant and increasing plant stress. This stress causes the potato plants to be more susceptible to fungal and bacterial diseases. There is also a correlation of root lesion nematodes with the incidence of Verticillium wilt. Five percent of Idaho growers consider this pest to be important [11].

Stubby root nematodes are migratory ectoparasites and are found in sandy, moist, cool soils. Damage is profoundly influenced by soil moisture and is greater in wet seasons. These nematodes are important parasites of potatoes, not so much for the direct damage they cause, but for the tobacco rattle virus they transmit to potatoes. This virus causes a disease of potato tubers called corky ringspot. (See discussion below.) Nematode problems occur mostly in isolated sandy soil areas of southern Idaho. These nematodes have wide host ranges, making management with crop rotation difficult and relatively ineffective. Stubby root nematode is mobile in the soil and may traverse larger vertical distances, making enumeration and determination of a threshold level difficult. They may survive cold winters by migrating below the freeze line and undergoing dormancy [11]. Stubby root nematode is a problem in Idaho and Washington. In Idaho, stubby root nematode infests approximately 50,000 acres of potato [27].

*Corky Ringspot*

Corky ringspot disease, also referred to as spraing, produces dark-brown “corky” necrotic areas in the form of arcs or diffuse brown spots within potato tubers. The causal agent of the disease is tobacco rattle virus that is vectored by stubby-root nematodes. Damage to tubers caused by corky ringspot disease is considered a quality defect by the potato industry, and tubers with more than one 33 mm diameter internal arc or spot per 28 g of tuber tissue are culled. Crops in which more than 6% of the tubers are graded as culls due to corky ringspot damage are often rejected or substantially downgraded in value [20].

*Weeds*

Weeds are considered one of the three most serious pests in potato production, causing 15% or more in yield losses if not controlled [11]. While fumigation is not targeted for weed control, can provide 50% of early weed control [8]. Weeds in potato include volunteer grains, grasses and broadleaf weeds. Primary target weeds in potato include nightshade (including volunteer potatoes), redroot pigweed and several other broadleaf and annual species [11]. Weeds can be hosts of major insect pests, viruses and nematodes, and fungal diseases [8].

*Fumigant Use*

Metam sodium was shown to be effective against Verticillium wilt as early as 1955-57, when trials were conducted in the Klamath basin of Oregon on fields that had experienced severely reduced yields. Researchers had estimated that in 1957, losses from Verticillium wilt in the Klamath area was at least
500,000 sacks of potatoes. Further, the researchers found that the disease suppressive effects of metam sodium lasted two or more years [14].

It is estimated that 90% of potato acreage in Washington State, 82% in Oregon and 50% in Idaho is fumigated [3]. Tables 2 and 3 show USDA estimates of dichloropropene and metam sodium use in potato production for available years from 1999-2010. In 2010, the use of chloropicrin and metam potassium is also reported for Idaho and Washington, but estimates are undisclosed to avoid the identification of individual operations in the data.

**Alternatives to Fumigants**

*Resistant Varieties*

Russet Burbank is the potato variety that has dominated potato production in major potato producing regions for nearly 100 years. Since the early 1990’s, the introduction of new russet types and processing varieties has gradually changed the mix of varieties grown [10]. In 2006, the percentage of the crop planted to Russet Burbank in Idaho, Oregon and Washington was 66, 26 and 35, respectively [17]. Table 4 shows the percent of potato acreage planted by variety in Idaho, Washington and Oregon for 2006.

Russet Burbank is moderately susceptible to Verticillium wilt [17]. Since 1984, a series of successful potato cultivars possessing varying levels of either resistance or tolerance to Verticillium wilt have been released. Most of these cultivars have been utilized in niche markets (e.g. Frontier Russet, Gemchip, Chipeta, Gem Russet, Ida Rose and Bannock Russet). However, two cultivars are emerging as cultivars with widespread appeal. Ranger Russet possesses a degree of tolerance to Verticillium wilt and Alturas is resistant to Verticillium wilt. Both Ranger Russet and Alturas achieve higher yields than Russet Burbank [18].

Resistance to Columbia root-knot nematode has been introduced into the potato breeding population which was found to prevent economic damage to the tubers as the nematodes failed to penetrate the tubers. Researchers concluded that the resistant breeding line could be grown in Columbia root-knot nematode infested ground without fumigation and that it lowers nematode populations dramatically compared to Russet Burbank [13]. However, researchers in the Pacific Northwest have not observed adequate levels of resistance to Columbia root-knot nematode [27].

The lack of success with Verticillium resistant cultivars is related to the difficulty in replacing Russet Burbank, the variety upon which the potato industry in the Pacific Northwest was standardized, and the fact that growers have been able to manage soilborne diseases [18].

*Green Manures*

Green manures are crops that are planted in the fall or early spring after the previous crop has been harvested but before planting the next potato crop. They are incorporated into the soil before they reach maturity. Research conducted in Idaho has shown that green manure crops have potential for control of nematodes and disease such as Verticillium wilt [8]. Incorporation of cover crops, including green manures and organic amendments, into fields before planting has shown potential as a management tactic for Verticillium wilt. Several crops have been investigated, including barley, broccoli, canola, mustards, corn, oat, sudangrass and winter pea, with variable results. Research is needed to
determine the host range of V. dahlia strains for prospective green manures, and to confirm the efficacy of green manures and organic soil amendments in different production. The use of green manures may require removing areas from production for a full season prior to planting potatoes [10]. Researchers have demonstrated that once a suppressive effect has been established, through 2-3 successive years of green manure treatments, a green manure treatment for a single season is sufficient to either maintain or to re-establish the control of Verticillium wilt of potato [21]. However, sudangrass, for example, when used as a green manure treatment, may be harvested in midsummer as a cash crop, with the regrowth used as a green manure in the late fall [18]. Alternatively, field studies demonstrated suppression of Verticillium wilt and increased potato yields compared to fallow treatments using sweet corn as a green manure for 2 or 3 seasons [22]. An additional benefit of green manures and cover crops may be increased yields beyond the effects of Verticillium control, possibly due to the addition of organic matter to soils [18].

The use of green manures has also been demonstrated to provide control of nematodes in potato [29]. Researchers caution that the selection of variety is critical to achieving optimal results [27].

**Soil Solarization**

Soil solarization is a nonpesticidal method of controlling soilborne pests by placing plastic sheets on moist soil during periods of high ambient temperature. The plastic sheets allow the sun’s radiant energy to be trapped in the soil, heating the upper levels. Solarization during the hot summer months can increase soil temperature to levels that kill many disease-causing organisms (pathogens), nematodes, and weed seed and seedlings. The practice is restricted to hot, dry climates and is a function of soil texture, soil temperature, soil moisture, and the amount of cloud cover and rainfall [10].

**Crop Rotation**

Selecting rotational crops that allow growers to manage weeds, insects, or disease pathogens that are hard to control in the potato crop is an integral part of an integrated pest management strategy. For example, rotating wheat and/or barley with potatoes allows growers to use herbicides that are more effective at controlling nightshade weeds, as potato and nightshade are closely related. Rotations of 4 to 5 years helps reduce the severity of Verticillium dahlia, Rhizoctonia, scab and nematodes [8]. Crop rotations of three to four years to non-susceptible crops can effectively reduce soil populations of V. albo-atrum, but generally not V. dahlia, as microsclerotia of V. dahlia may survive for long periods in soil. Rotation to non-susceptible hosts can reduce incidence of verticillium wilt and increase crop yields [10].

**Nematicides**

Potato growers currently have two available nematicides: ethoprophos (Mocap) and oxamyl (Vydate). Oxamyl is a systemic nematicide that is very effective in controlling all nematodes. However, oxamyl is sensitive to pH which can be a constraint to its use. Further, oxamyl has a short half-life, requiring multiple applications during the growing season. Ethoprophos may be used to treat root-knot nematodes, both Columbia and northern. Oxamyl has acceptable efficacy on low populations. In trials comparing metam sodium and oxamyl, no statistically significant difference was found, though the test plots had relatively low nematode pest pressure [28]. Preliminary testing of fosthiazate has been conducted in the PNW on root-knot nematodes and results show good efficacy. Oxamyl effectively
control stubby-root nematodes [8]. There have been promising results for new nematicidal compounds, but none should be considered stand-alone treatments, and they require multiple applications [27].

**Organic Production**

In order to be eligible for USDA organic certification, growers must farm on land to which no synthetic fertilizers or pesticides have been applied for a minimum of three years. In 2011, there were 13,258 acres of certified organic potatoes in the U.S., or 1.21% of total US potato acreage [24]. The pest management strategies of organic producers are best characterized as “biointensive” systems utilizing cultural, physical, mechanical and biological methods, as well as some pesticides that are approved for use in certified organic production. These methods are intended to prevent pest establishment or population increases. The primary strategies used by organic potato farmers are: long crop rotations (e.g. 5-7 years in Idaho); avoiding planting in fields with known pest problems; sanitation of equipment, seed, water and personnel to prevent the introduction of weeds, nematodes and soilborne diseases; selection of varieties with tolerance to nematodes, diseases and insects and other characteristics to be more competitive with weeds and other pathogens; cover crops and green manures; crop residue management; weed host control; irrigation management, among other strategies [23].

**Estimated Benefits of Soil Fumigants**

Researchers have identified green manures combined with nematicide treatment as the next best alternative to fumigation for Idaho, where nematode pressure is lower. The estimated benefits of soil fumigation in Idaho production compared to the next best alternative are calculated assuming a 12% yield benefit from soil fumigation [25] and costs similar to fumigation. Research in the Columbia River Basin showed that while total yields were 17% higher with metam sodium fumigation, yields of US #1 grade potatoes were 35% greater [30]. No feasible alternative was identified for Washington and Oregon, where pest pressure is higher due to the longer growing season and greater use of irrigation [27].
References

17. USDA NASS, 2006, Crop Production, 


Cover Photo Credit: Verticillium wilt symptoms in potato from [26].
**Table 1. US Potato Production by State 2012**

<table>
<thead>
<tr>
<th>State</th>
<th>Acres Planted (1000)</th>
<th>Acres Harvested (1000)</th>
<th>Yield (cwt)</th>
<th>Production (1000 cwt)</th>
<th>Value of Production ($1000)</th>
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<td>344</td>
<td>412</td>
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<td>164</td>
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<td>84</td>
<td>300</td>
<td>25,200</td>
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<td>Colorado</td>
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<td>59.3</td>
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<td>41.7</td>
<td>550</td>
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<td>181,187</td>
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<td>US</td>
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<td>1,131.9</td>
<td>409</td>
<td>462,766</td>
<td>3,993,815</td>
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Source: [2]

**Table 2. Dichloropropene Use in Potato Production, Percent of Planted Area Treated**

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<th>2010</th>
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<td>5</td>
<td>5</td>
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<td>Oregon</td>
<td>35</td>
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<td>Washington</td>
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<td>17</td>
<td>12</td>
<td>20</td>
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</table>

Source: [15]

**Table 3. Metam Sodium Use in Potato Production, Percent of Planted Area Treated**

<table>
<thead>
<tr>
<th>State</th>
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<th>2001</th>
<th>2003</th>
<th>2005</th>
<th>2010</th>
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<td>Minnesota</td>
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D-undisclosed to avoid publication of data for individual operations

Source: [15]
Table 4. Percent of potato acreage planted by potato variety in 2006

<table>
<thead>
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<th>Variety</th>
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<th>Washington</th>
<th>Oregon</th>
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<tr>
<td>Russet Burbank</td>
<td>66</td>
<td>34.9</td>
<td>26</td>
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<tr>
<td>Russet Norkotah</td>
<td>10.2</td>
<td>14</td>
<td>20.4</td>
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<td>Not Reported</td>
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<td>Ranger Russet</td>
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<tr>
<td>Umatilla Russet</td>
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<td>2.2</td>
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<tr>
<td>Alturas</td>
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<td>5.5</td>
<td>3.7</td>
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<tr>
<td>Others</td>
<td>8.9</td>
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Source: [17]
### Table 5. Estimated Benefits of Fumigants for Potatoes in the Pacific Northwest

<table>
<thead>
<tr>
<th>State</th>
<th>Acres</th>
<th>Value of Yield Increase Per Acre</th>
<th>Cost Per Acre</th>
<th>Total</th>
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<tr>
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<td>$329</td>
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<td>Washington</td>
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<td>$4245</td>
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<td>Oregon</td>
<td>51,220</td>
<td>$2901</td>
<td>$300</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>372,220</strong></td>
<td></td>
<td></td>
<td><strong>$783,901,640</strong></td>
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</table>

Calculated assuming 50% of acres in Idaho are fumigated, 90% in Washington and 82% in Oregon [8] and 12% yield benefit from fumigation [25]. Acreage and prices based on estimates for 2012 [2].
Figure 1. US Potato Production 1930-2010, Area Harvested and Total Production