Plant Biotechnology: Current and Potential Impact For Improving Pest Management In U.S. Agriculture An Analysis of 40 Case Studies

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Insect/Viral Resistant Potato

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17. POTATO
Insect/Viral Resistant

Production
Northwestern states of Idaho (395,000A), Washington (170,000A) and Oregon (56,000A) have 621,000 acres planted to potatoes, representing 43% of U.S. acreage. Fifty-four percent of U.S. production of potatoes is produced in these three states: 25.6 billion pounds per year. The value of potato production in the three states is $1.3 billion per year [1].

Insect/ Mite/ Nematode Pests

The most damaging insect pest in the Northwest is the green peach aphid, which transmits the potato leafroll virus, which causes the damage symptom tuber net necrosis, as well as other potato viruses [2]. The Colorado Potato Beetle, which feeds on foliage in both larval and adult stages, is a major pest in all three states [2]. Insect pest species that attack tuber or seed pieces appear either sporadically or on limited acreage (wireworms, flea beetles). Nematodes are a major problem on portions of northwest potato acreage. Nematodes are one of the major limiting factors for potato production in the Northwest. [25]

Two spotted spider mites occur everywhere in the western U.S.; and significant damage to potatoes occurs from their feeding [2]. The mites injure potato vines by puncturing the surface cells of leaves. Severe injury may lower yields by lowering the capacity of plants to perform photosynthesis. Mites are often kept under control by natural enemies, including insect predators such as pirate bugs as well as predatory mites. Outbreaks of mites sometimes occur when natural enemies are destroyed by insecticides applied for aphids [2]. Dry and dusty conditions are known to favor mite growth and survival and can provide conditions that outstrip the ability of natural predators to keep mites in check. Another factor contributing to spider mite infestations in potatoes includes proximity to alternate hosts especially corn.
Aphids

The green peach aphid overwinters as eggs on woody plants or trees, predominantly peach and certain weed species. If conditions are favorable for aphid development, a single tree potentially can produce enough winged aphids to initiate economic infestations on at least 500 acres of potatoes [3]. In spring, wingless aphids, called stem mothers, hatch. They and all their descendants of the spring and summer are females and reproduce without mating, giving birth to live young. Winged spring migrants are produced and leave the host plant in search of suitable summer hosts – such as potatoes [4]. At the height of the flight, 2.5 million aphids can blanket an acre of potatoes [5].

Winged aphids alight at random since they cannot distinguish a host from a non-host plant from a distance. To find a suitable host, winged aphids feed for short periods on plants on which they land. Once an acceptable host plant is found, the spring migrants settle down and reproduce. The summer reproductive aphid population is wingless. As the day length shortens, fall migrants are produced, both males and females. They return to a winter host plant on which fertilized overwintering eggs are laid [4].

Green peach aphid eggs are produced by sexual females in the fall, but otherwise the cycle is continued with females giving birth to females for 10 to 25 generations during the growing season. Each aphid is capable of producing 30 to 80 nymphs over a period of 10 to 20 days.

Aphid movement each year is characterized by three major flights [39]. Aphids from the spring flight often land in potatoes, but go unnoticed due to their low numbers. The larger summer flight is responsible for most of the wingless colonization that takes place in potato fields. Wingless aphids build in numbers throughout July in most years and decline precipitously without intervention sometimes in late July or August, probably due to an interaction of physical and biological factors. A flight occurs in late August to early September when aphids move back to their winter hosts.
Data from research trials in the Pacific Northwest have demonstrated that natural enemies of aphids including predators, parasites, and entomophagus fungi can colonize potato fields and limit aphid outbreaks in the absence of insecticides [40][41]. Such biological factors can maintain aphid populations below levels that result in direct plant damage, but are generally insufficient to prevent transmission of virus in susceptible varieties [42]. Insecticide sprays in potato fields often eliminate these predators causing increased buildup of aphid populations [4]. Idaho has less of an aphid problem than Oregon and Washington because winters are harsher and, as a result, there are fewer overwintering aphids.

Potato leafroll virus is transmitted by aphids. After ingestion of plant sap infected with potato leafroll virus, virus particles pass through the aphid’s gut wall and into the bloodstream. From there, the virus enters the salivary glands, and the aphid can then transmit it to another plant while feeding. Once potato leaf roll virus is acquired, an individual aphid retains the virus throughout its life [4].

The green peach aphid is non-gregarious. As aphid populations increase, some individuals begin to crawl away from the plant to avoid other aphids. If the plant is infected by potato leaf roll virus, these aphids will spread the virus to additional plants.

The virus is spread in enlarging concentric circles around the primary inoculum source as the aphids move from plant to plant. These expanding infestation sites will coalesce and may engulf entire fields within a few weeks if the aphid populations are not controlled [7].

The virus moves within the potato plant, from one cell to another and multiplies in most cells into which it moves. The virus moves rapidly through growing regions and other regions of food utilization in the plant, such as tubers. Tubers from plants that become infected during the growing season can develop net necrosis in which cells are killed, leaving a network of coarse brown strands throughout the tuber.

Potato leaf roll virus infection symptoms include leaf rolling, stunted plants, and discoloration of leaves, which become stiff, dry and leathery. Potato leaf roll virus infections reduce potato plant vigor and can result in high yield losses [6].
The Russet Burbank potato variety is the dominant variety in the Northwest. The Russet Burbank is susceptible to potato leaf roll virus and the associated tuber net necrosis. The green peach aphid is the only important vector of the virus in the West and, because of this, is the key insect pest of Russet Burbank potato crops [3].

Incidence of potato leaf roll virus infection routinely approaches 100% in potato crops in the Northwest when insecticides are not used [7]. Yields of potato leaf roll virus-infected plants may be reduced by as much as 50% [19]. Potato yields are reduced about 0.5% for each percent of potato leaf roll virus infection [33]. The yield at harvest is reduced if the potato plants are infected at an early stage and fewer and smaller tubers than normal are produced [33]. Late season aphid damage to plants is not always apparent since the plants are drying out. However, net necrosis symptoms will show up during storage [8][36]. If the amount of net necrosis in the tubers exceeds 5%, the potatoes may have to be diverted from the frozen, chip, dehydrated and flour markets as well as the fresh market to the cullage market [33]. Even at levels of less than 5%, growers can be docked. Even effective insecticide programs do not totally prevent the transmission of the virus.

By the end of the 1920’s, significant evidence indicated that aphid species were responsible for transmission of potato virus diseases. However, suppression of the virus by eradicating the insect species was not attainable [11].

Idaho tried to eradicate the green peach aphid from a potato growing area adjacent to the mountains by locating and removing peach trees that harbored the pests. Unfortunately for the growers, only one-quarter of the 4,600 potential overwintering sites, peach trees, could be removed [11].

During the last 5-6 years a major increase in aphid problems has occurred in the Pacific North West [36]. 1999 populations were very large with a huge aphid influx early in the season. Decreases in yield quality due to potato leaf roll virus and the resulting net necrosis occur routinely and are increasing. In 1993 1.2% of Washington Russet Burbank potatoes were rejected for being out of grade due to unacceptable occurrence of net
necrosis [26]. A recent study of 78 fields of late harvest potatoes in Washington determined that 24% of the potatoes were infected with potato leaf roll virus [24][34]. 10-25% of the potatoes in Washington are normally infected [34]. Because of the increasing aphid populations and severe potato leaf roll virus in recent years, extension entomologists have begun recommending even more intensive measure such as insecticide applications every 7 to 10 days to ensure adequate aphid control [38].

The Colorado Potato Beetle
The Colorado Potato Beetle is the major defoliating insect pest of potatoes in the Northwest. It is thought that the Colorado Potato Beetle originated in Mexico and gradually moved north [10]. In the early 1900’s, the Colorado Potato Beetle appeared in Nez Perce county in Idaho (the only county in which it was known west of the Rocky Mountains) [11]. From 1910 to 1912, some beetles were reported in different parts of eastern Washington, and by the end of 1913, they were abundant in Washington. In 1916, the beetle appeared in eastern Oregon [11].

If uncontrolled, the Colorado Potato Beetle can defoliate completely all potato plants in a field by mid-season [25][10]. Loss of leaf surface reduces the ability of plants to produce carbohydrates for storage in tubers. Heavily defoliated plants have reduced yield and lower tuber quality. Yield losses due to Colorado Potato Beetle can exceed 85% [30][31][32].

Colorado Potato Beetles overwinter as adults in their field of origin, in uncultivated areas adjacent to the field and in wooded areas away from it. The adult Colorado Potato Beetle spends the winter buried four to ten inches deep in the soil. Female beetles almost always are inseminated before overwintering, and, as a result, need not mate before dispersal in the spring. Within a few days of colonizing a field, the beetles feed and begin to deposit egg masses composed of 25-50 eggs [10]. Each female can produce about 450 eggs. A single larva consumes about four square inches of foliage before dropping to the ground to pupate. The next generation of adults emerges from the pupae in the soil and begins to lay eggs.
In fields where potatoes were grown in the previous year, overwintering adults emerge in close proximity and colonize fields by walking from adjacent areas. If the field has been rotated to another crop, the adult beetles need one to two weeks to regenerate their flight muscles (wings) [10]. Weeds and alternative host plants serve as refuges for Colorado Potato Beetle; there is always at least a small population on these hosts that will move to potato plants when they are available.

If beetles emerge in the spring in a habitat containing host plants such as potatoes, they rarely will fly; instead, they immediately will feed. If starved, beetles first will walk to find hosts, then resort to flight. The flight may continue for two weeks and result in movement of several miles. The adult beetles can go without feeding for a month.

Insecticide Use
Arsenate of lead was used for control of the Colorado Potato Beetle in the Northwest from about 1920 until the introduction of DDT in 1945 [11]. Another benefit from the use of DDT was a significant reduction in the aphid population. In 1948, parathion was introduced and proved outstanding in its control of aphids. By this time potato growers had adopted DDT for potatoes, and, as a result, the application of arsenic was nearly eliminated [11].

By 1963, parathion and DDT were no longer as effective in controlling aphids and Colorado Potato Beetle. They were replaced by endosulfan and endrin for Colorado Potato Beetle control. The systemic insecticides, disulfoton, phorate, mevinphos, and phosphamidon were introduced for aphid control. Methamidophos was available in the summer of 1973 in time for many potato growers to treat aphid populations that had gotten out of control [11].

A major chemical breakthrough came in 1975 when aldicarb began to be applied to potatoes. Aldicarb granules incorporated into the soil at planting provides good control for aphids and Colorado Potato Beetle for the first 90 days of the season [11]. Aldicarb at planting was a popular practice followed by foliar sprays with methamidophos, endosulfan and pyrethroids.
When aldicarb is applied in moist soil, the active ingredient is absorbed in soil water and the pesticide is absorbed rapidly by the germinating seedlings or by established roots. The toxicant moves upward through the vascular system to all plant parts by systemic action. Pests feeding on leaves or sap are killed by consuming low concentrations of the pesticide in the plant tissue. The persistence of aldicarb’s pesticidal activity is estimated at 10 weeks in potato plants [12].

*Bacillus thuringiensis* var. *tenebrionis* produces a crystal protein (Cry3A) that is insecticidal to Colorado Potato Beetle [13]. When susceptible larvae feed on potato foliage treated with Bt, an endotoxin specific to Colorado Potato Beetle is released in the gut. This endotoxin inhibits feeding and ultimately causes death [14]. Bt sprays can be used effectively to maintain Colorado Potato Beetle populations below economic injury levels. However, the Bt sprays have several shortcomings: they are only effective against early Colorado Potato Beetle instars; they have little residual activity; and they have stringent requirements for precise application timing and other conditions for optimum activity.

Insecticides for aphid control in potato include soil-applied systemic materials, as well as foliar sprays. Systemics, applied at planting or as side-dressing, control aphids for about six to eight weeks or longer after application. Many growers utilize soil applied systemic insecticides early in the season, followed by soil or foliar-applied insecticides when efficacy begins to decline [15].

Systemic insecticides prevent aphid populations from building up, but they do not kill aphids quickly enough to prevent winged migrants from transmitting viruses. Insecticides are slow to kill aphids, often taking 24-48 hours to killed winged and mature wingless aphids. If large numbers of migrants are flying in from virus reservoirs, the incidence of leafroll or other viruses may be high despite treatment with systemics. If there are infected plants within the field, winged aphids from outside may live long enough to acquire virus from an infected plant and transmit it to a healthy one, even though both plants contain a systemic insecticide. Foliar sprays must be used if control is needed after a soil application has ceased to provide adequate control.
In the Northwest, the use of aldicarb, carbaryl, carbofuran, disulfoton, endosulfan, imidaclorpid, permethrin, azinphos-methyl, diazinon, dimethoate, esfenvalerate, and methamidophos are targeted at beetles and aphids [20][25]. Ethoprop is targeted at nematodes and wireworms while propargite is targeted at mites [23]. Phorate is targeted at aphids, beetles, and wireworms [20], [11], [25]. Table 17.1 shows insecticide use estimates for the individual states of Idaho, Oregon, and Washington.

A 1999 survey of potato producers in Idaho, Oregon and Washington indicated a usage of 2.0 million pounds of insecticides [21]. Table 17.2 shows summary estimates for each insecticide active ingredient for which usage was reported. Of the total usage, 1.4 million pounds is estimated to be targeted at control of the Colorado Potato Beetle and aphids, with the remaining 0.6 million pounds targeted at other pests (propargite [mites], ethoprop [wireworms], and fonofos [wireworms, symphylan]). Two thirds of phorate’s use is assumed targeted at beetles and aphids with the remainder targeted at wireworms. According to the 1999 survey, approximately 94% of the potato acreage in the three states is treated with insecticides (581,000 acres). The survey summarizes the number of applications per acre for each active ingredient. Several of the active ingredients are used on the same acre more than once during the growing season. Each treatment of an acre with an insecticide is referred to as an “acre treatment.” Table 17.2 summarizes the total number of acre treatments by active ingredients for the three states. A total of 1.178 million acre treatments were made with insecticides for Colorado Potato Beetle and aphids, implying an average of 2.0 insecticide applications per treated acre. Each application is estimated to cost $6.25 per acre [22], implying an average application cost of $12.50 per treated acre. Table 17.2 also displays estimates of the average price of each insecticide active ingredient used for Colorado Potato Beetle/aphid control. These estimates were derived from a survey of chemical dealers in Idaho in 1999 [22]. By multiplying these average unit prices by the total poundage of each active ingredient, it is estimated that potato growers in the three states spent $26.3 million for insecticides to control the Colorado Potato Beetle/aphid in 1999. (See Table 17.2.) This implies an average cost of insecticide active ingredient of $45 per treated acre. The total cost of insecticides and application for Colorado Potato Beetle/aphid control is estimated at $57.50 per acre in 1999.
Insect Resistant Potato

In the 1980’s scientists transformed Russet Burbank potato plants through insertion of a gene from the bacteria *Bacillus thuringiensis*. The transformed potato plants express the Bt Cry3A protein throughout the plant [13]. The Colorado Potato Beetle ingests the protein endotoxin when feeding on the plant. The endotoxin is activated in the Colorado Potato Beetle’s gut by enzymes. The endotoxin binds to membranes in the gut, and pores are formed. Cells in the gut rupture and the Colorado Potato Beetle larvae die.

The Cry3A delta endotoxin produced in potatoes is identical to that found in nature and in commercial Bt formulations. However, these potatoes produce the Cry3A delta endotoxin throughout the plant for the length of the growing season at a level sufficient to control all life stages of the Colorado Potato Beetle [13][16].

Field experiments demonstrated that Bt potatoes are protected season long from all Colorado Potato Beetle life stages [13]. Growers who use Bt protected plants do not require chemical insecticide applications to control Colorado Potato Beetle [16]. Surviving larvae have not been found in field experiments despite numerous test plots around the country [29]. The transgenic plants express a very high concentration of Bt endotoxin relative to susceptibility of Colorado Potato Beetle and it is expressed constantly throughout foliage and over time [29]. Fifteen days after exposure, 99% of beetles on the transgenic plants were dead [13].

The transformed potato plants have agronomic and tuber characteristics consistent with standard Russet Burbank plants [13]. In taste tests, the transformed potatoes compared favorably with control Russet Burbank potatoes [13]. Experiments showed that 100% of conventional potato plants not protected by insecticides were defoliated by Colorado Potato Beetle larvae and adults in mid to late July, whereas, no Bt potato plants and less than 5% of non-Bt potato plants protected with insecticides were defoliated [35] (see figure 17.1). Results from the field trials indicated that the Bt potatoes were highly effective in reducing the abundance of Colorado Potato Beetle populations and provided better control than bi-
weekly sprays of permethrin or early and mid season applications of systemic insecticides (phorate, disulfoton) [35].

In contrast to the Bt potatoes the use of a broad-spectrum insecticide had a broad and unintended impact on non-target beneficial insect predators [35]. Applications of the insecticides significantly reduced the populations of several major generalist predators such as spiders, big-eyed bugs, damsel bugs, and minute pirate bugs which resulted in significant increases in the abundance of aphids on treated plants [35].

Yield data for 1996 and 1997 commercial fields (101 fields) indicated that fields of New Leaf cultivars produced yields approximately equal to yields on non-Bt Russet Burbank cultivars treated with insecticides.

**Virus Resistant Potato**

Russet Burbank potatoes have been transformed via *Agrobacterium tumefaciens* with potato leaf roll virus (PLRV) double gene constructs known as orf1/orf2 or the potato leafroll virus resistance gene [7].

Monsanto also developed a transgenic potato resistant to potato virus Y, which is also a major problem for U.S. potato growers. However, this review focuses only on PLRV resistance.

The New Leaf Plus potato also contains the Bt endotoxin gene. Induction of resistance to potato leaf roll virus infection by the orf1/orf2 gene is not clearly understood at present. The orf1/orf2 gene does, however, induce virus resistance by a non-toxic mode of action [18]. The presence of the gene in the plant interferes with the viral replication process.

Yields of non-transformed untreated potatoes were markedly reduced by leaf roll disease while there was little or no effect of the disease on the transgenic plants. The transgenic plants remain essentially free of leaf roll disease and net necrosis under natural conditions.
and even when they have been artificially inoculated as young plants in the fields with potato leaf roll virus [28].

Experiments determined that 87% of untreated conventional potatoes were infected with potato leaf roll virus and 48% showed signs of net necrosis. Transformed lines showed 1-2% infection with 1-2% net necrosis [27]. These experiments show that very high levels of resistance to potato leaf roll virus are achieved by expression of the viral gene in potato plants.

The transgenic potatoes do not kill aphids, but are protected from the virus that aphids transmit. As a result, aphids can be tolerated at much higher numbers. It is estimated that aphids in excess of 10 aphids per leaf (on average) can exist on potatoes without causing feeding damage. One key criterion for treating high populations of wingless aphids in the transgenic potatoes is whether they have reached a point of crowding such that immature aphids have started to develop wings. Such populations should be treated to prevent generating large numbers of winged adults that may contaminate other fields.

 Estimated Impacts

If Northwestern potato growers planted transgenic potatoes that contain the Bt and potato leaf roll virus genes, which effectively kill the Colorado Potato Beetle and prevent infection from the virus, they could stop applying insecticides for the control of the Colorado Potato Beetle and green peach aphid. In addition, it is estimated that 50% of the use of propargite for mite control would not be necessary due to the conservation of natural mite predators following the cessation of sprays for the Colorado Potato Beetle and green peach aphid [36] [37]. The total reduction in insecticide use is approximately 1.45 million lbs/yr (see Table 17.2) with an associated cost savings of $27 million/yr, which represents a savings of $57.50/A (including application costs). It is assumed that a technology fee of $46/A will be charged which implies a per acre net reduction in insect control costs of $11.50/A or $6.7 million in the aggregate.
It is estimated that current average incidence of potato leaf roll virus in the Pacific Northwest is 10% which represent an average yield loss of 5%. The planting of the potato leaf roll virus resistant potato is assumed to reduce the incidence of potato leaf roll virus to 2%, which would represent a 1% yield loss. Thus, the planting of the potato leaf roll virus resistant potato is expected to increase Pacific Northwest potato yields by 4% which represents a 1,680 lb. increase per acre in production with an increased value of $84/A which implies an aggregate increase in production value of $52 million/yr (1 billion lbs). These estimates were assigned to Oregon, Washington and Idaho in proportion to acreage.

These results can be compared to Monsanto’s analysis of grower experiences in the Northwest [43]. Monsanto reports that growers of the Bt/potato leaf roll virus resistant potatoes (New Leaf Plus) saved $92/A in 1998 and $59/A in 1999 in insecticide costs in comparison to growers who grew conventional varieties (these estimates do not include the technology fee). Monsanto estimated economic losses to growers which resulted from downgrades due to net necrosis. In 1998 the economic losses were $40/A higher in the conventional potatoes than the transgenic fields while in 1999 the losses were $121/A higher in the conventional fields. [43]

Monsanto commercialized New Leaf Plus potatoes which contained the Bt/potato leaf roll virus genes in 1998 (New Leaf potatoes which contained the Bt gene only were commercialized in 1996.) In 1999 the transgenic potato was planted on 4% of US acreage declining to 2% in 2000 due to processor objections to buying genetically-engineered potatoes [44][9]. Early in 2001 Monsanto announced the closing of its potato division and ceased sales of the transgenic potatoes although all transgenic variety registrations remain in place [45].
Figure 17.1

Defoliation of Potato Plants by Colorado Potato Beetle

Source [13]
Table 17.1
Insecticide Use in Potato Production: Idaho, Oregon, and Washington

1999

A. Idaho

<table>
<thead>
<tr>
<th>Active Ingredient</th>
<th>% Acres Treated</th>
<th>Number of Applications per Acre</th>
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<td>Carbaryl</td>
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Source [21]
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Source [21]

### C. Washington

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Source [21]
TABLE 17.2 Insecticide Use: Potato Production, Northwest Summary (1999)

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<th>For Colorado Potato Beetle/Aphids</th>
<th>Lbs AI(^1) (000)</th>
<th>$/Lb AI(^2)</th>
<th>$/Yr(^3) (000)</th>
<th># Acre Treatments(^4) (000)</th>
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<tr>
<td>Esfenvalerate</td>
<td>2</td>
<td>202.34</td>
<td>405</td>
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<td>Imidacloprid</td>
<td>7</td>
<td>317.50</td>
<td>2,222</td>
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<tr>
<td>Methamidophos</td>
<td>453</td>
<td>21.50</td>
<td>9,740</td>
<td>466</td>
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<tr>
<td>Permethrin</td>
<td>6</td>
<td>50.50</td>
<td>303</td>
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<tr>
<td>Phorate (.67)</td>
<td>437</td>
<td>10.50</td>
<td>4,588</td>
<td>157</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,413</strong></td>
<td></td>
<td><strong>26,330</strong></td>
<td><strong>1178</strong></td>
</tr>
</tbody>
</table>

**Other Pests**

<p>| | | | | |</p>
<table>
<thead>
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<tr>
<td>Ethoprop</td>
<td>300</td>
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<tr>
<td>Phorate (.33)</td>
<td>216</td>
<td></td>
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<tr>
<td>Propargite(^1)</td>
<td>74</td>
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<tr>
<td>Fonofos</td>
<td>4</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>594</strong></td>
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</tbody>
</table>

**GRAND TOTAL** 2,007

\(^1\) Source [21]  
\(^2\) Derived from [22]  
\(^3\) By multiplication  
\(^4\) Derived from [21]
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