

## ALTERNATIVE NATURAL RUBBER CROPS: WHY SHOULD WE CARE?

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Natural rubber is a strategic raw material essential to the manufacture of 50,000 different rubber and latex products. Until recently, natural rubber has been produced solely from a single species, the rubber tree (*Hevea brasiliensis*), which is grown as genetically similar clones in tropical regions and harvested by hand. Developed countries import all the natural rubber they require: >1.2 megatons/year by the U.S. and >12 megatons/year globally. Steadily increasing demand cannot be met in the future by the rubber tree alone, and viable alternative crops that can be established on farms and managed with mechanized equipment are required. If we fail to accomplish this goal in the near future, adverse economic consequences are predicted. However, while the introduction of any new crop is extremely challenging, a new rubber crop requires parallel coordinated expansion of farm acreage and processing capacity, initially feeding high-value niche markets suited to small-scale production, but which can gradually transition to address the much larger commodity markets. Sustainability of new rubber crops depends on valorization of the entire plant and environmentally-friendly processing. In the long term, the rubber from alternate rubber crops, especially more heat-stable derivatives such as epoxidized rubber, may supplement sections of the market share currently occupied by various synthetic rubbers with enormous carbon footprint savings.

**Key words:** Buckeye Gold; Domestic crops; Economic security; Guayule; Hevea; Kazak dandelion; Natural rubber; Rubber dandelion; Rubber root; Russian dandelion; Sustainability

### NATURAL RUBBER IMPORTANCE

Current natural rubber (NR) supplies from tropical countries are insecure because of burgeoning global demand led by the industrialization of developing countries, labor shortages, and fungal crop diseases. Total rubber consumption increased 61.2% from 2000 to 2014, and demand is continuing to increase. In 2014, global NR consumption reached 12.159 megatons (mt), nearly a 6.8% increase from the previous year (1), and consumption is expected to continually increase due to rising demands from

emerging economies such as those of China, India, and Brazil. World NR consumption is expected to be 16.5 mt/y by 2023 (1) and to continue to increase thereafter. Predicted impending global natural rubber shortages are greater than the 1.2 mt imported annually by the U.S. As economies of rubber-producing Asian countries improve, they struggle to support low cost natural rubber production from plantations of *Hevea brasiliensis* (rubber tree), and acreage is replaced primarily with less labor-intensive oil palm (2). This is because natural rubber is harvested by

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hand, tapping the bark of the rubber trees to dribble the rubber-containing latex into small cups (3). About 11% of the latex is concentrated by dewatering before it is shipped to latex product manufacturers. The remainder is converted to solid rubber (by various methods) for products such as tires (tires consume ~70% of all natural rubber) (4). Replacement rubber tree acreage is established in poorer countries after first clearing more rain forest, a practice with an increasingly devastating ecological impact (5). Partly in response to this practice, the World Wildlife Fund is supporting a global deforestation moratorium. This is gaining traction, and Michelin is the first major tire company to commit to the moratorium (6). Widespread acceptance that additional deforestation in biologically-diverse rain forests is unacceptable will limit, or even prevent, the planting of new rubber tree plantations (7). The immediate requirement for new plantings to meet predicted demand in a five to seven year time frame requires new acreage of 32,817 square miles (8.5 million ha) (5), an area similar in size to Austria or the U.S. state of South Carolina. Thus, there is a critical need to establish sustainable, alternative rubber crops to supply the global natural rubber market in general, and U.S. industry in particular, before economically damaging disruptions in NR supply occur.

It is curious that the importance of natural rubber is largely unnoticed by all those not intimately involved in the industry even though it is a critical raw material essential to the manufacture of 50,000 different NR products, and all industrial, consumer, medical, and military sectors. Recognizing rubber's importance, a recent *Rubber Journal Asia* article asks, "What would industrial progress be without natural rubber? It's hardly imaginable" (8). The History Channel's *Modern Marvels* series states the issue even more directly, declaring: "Our four most important natural resources are air, water, petroleum and rubber" (9). Modern life is dependent upon natural rubber, and it cannot be replaced by petroleum-derived synthetic rubber in many high-performance applications. To put this demand in context, the 2014 global consumption of 12.2 mt is equivalent to the weight of approximately 11 full-grown, male African elephants every minute of the year. By 2030, the predicted demand of 30 mt/y will require the equivalent of 28 elephants/minute—all collected in little cups! At the moment, synthetic rubber (SR) occupies 55%

to 65% of the total rubber market, and increasing demand for these materials parallels the increasing demand for natural rubber. Natural and synthetic rubber materials are essential to virtually all manufacturing sectors, but all NR and a significant amount of SR used in the U.S. are imported, although the U.S. could manufacture sufficient SR to meet its internal demand. However, virtually all SRs are currently produced from non-sustainable fossil-fuel feedstocks and contribute heavily to pollution of air, soil, and all natural sources of water. Natural rubber can supplement synthetic rubber (currently responsible for ~90 mt of CO<sub>2</sub>/y) in some applications, supporting national goals of a sustainable and resilient bio-based economy (10).

## NATURAL RUBBER INSECURITY

Even without increasing rubber demand, the natural rubber supply is at risk because, unlike most other agricultural commodities, it depends on a single species grown as clonal scions on seedling rootstocks. A lack of genetic diversity makes any crop prone to failure. Only a very few closely related clones are used, a single genetically-identical clone can account for hundreds of thousands of hectares of production, many fungal diseases constantly infect the plantations/small holdings, and obviously the risk of crop failure is extremely high (11). South American Leaf Blight (SALB) (*Microcyclus ulei*), a fatal rubber tree fungal disease, prevents large-scale production in Brazil, the country of origin of this species (11-13). Work is in progress on finding SALB resistant germplasm, but it takes approximately 25 years to simply introduce each new clone, let alone replace the rubber tree acreage with resistant high-yielding clones. Thus, biodiversity of the natural rubber supply is essential for long-term sustainability and security.

## ALTERNATIVE NATURAL RUBBER CROPS

Two alternative rubber-producing species are under development to address rubber biodiversity and critical supply needs: *Parthenium argentatum* (guayule) (14) and *Taraxacum kok-saghyz*, (rubber dandelion, also known as Buckeye Gold, Kazak(h) dandelion, rubber root, Russian dandelion, TK, and TKS) (Figure 1 (a) and (b)) (15). Guayule is native to the Chihuahuan desert of North America, whereas



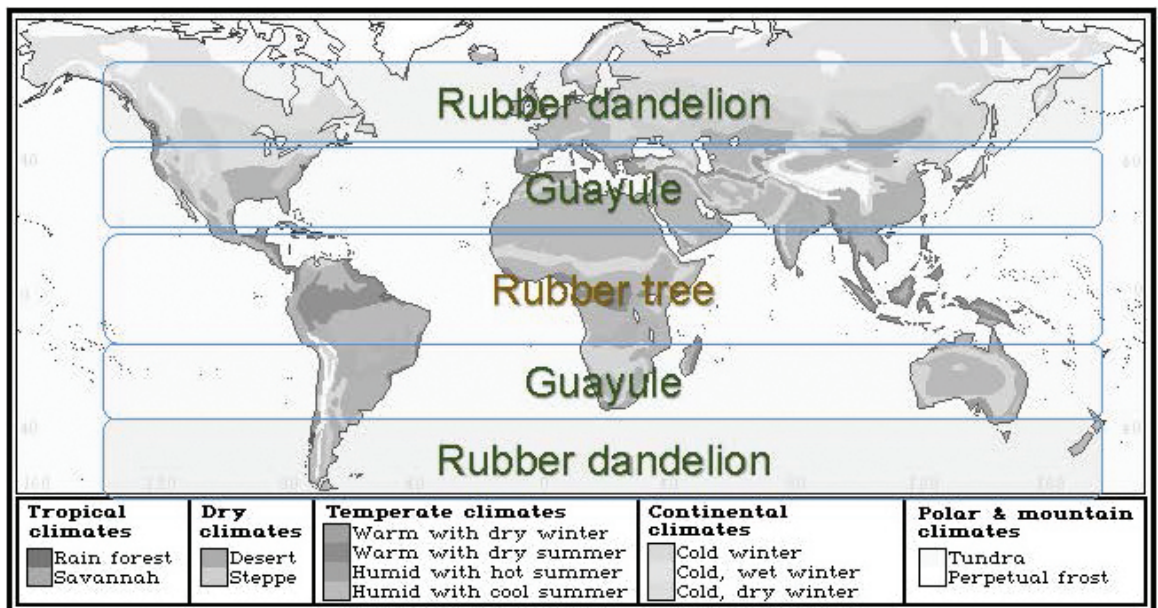
**Figure 1.** Field grown alternate rubber crops: (a) *Taraxacum kok-saghyz* (rubber dandelion) and (b) *Parthenium argentatum* (guayule).

rubber dandelion is native to Kazakhstan, Uzbekistan, and Northwestern China. The agricultural ranges of the rubber tree, guayule, and rubber dandelion are distinct, and the three species can cover most of the agricultural regions of the world (Figure 2). Both alternative species are being developed on farms and research centers in the U.S., Europe, and Asia to safeguard national manufacturing requirements and induce global price stability.

### NATURAL RUBBER DIFFERENCES

It is important to understand that rubber produced from different species is not the same (Table 1). This is analogous to starch from corn, potatoes, and rice, for example. Chemically, all starches are made of linear and helical amylose and branched amylopectin (16). However, the composition and macromolecular structure of starch from different

species differ, and their behavior, properties, and uses differ as well (16). Similarly, all natural rubber, chemically, is *cis*-1,4-polyisoprene, usually with a 2 to 3 unit *trans*-polyisoprene piece on the front end (17-19). However, molecular weight, macromolecular structure, intrinsic crosslinking, branching, and composition are species-specific and affect properties and uses (Table 1) (20-24). Plants make many *cis*-polyisoprenes, but they are only considered “rubber” if they are at least 100 isopentenyl units long, and at least 15,000 units are required for high quality rubber (>1 million g/mol molecular weight). It is well recognized that rubber is elastic and will revert to its original size and shape after deformation. However, what makes rubber such an irreplaceable material is its ability to stress-strain crystallize (22,25). This means that as rubber is stretched, its polymers change from a random to an ordered arrangement and effectively crystallize in the rubber matrix. This is evinced by the strength of the material rapidly increasing the more the material is stretched. This property can be deliberately increased by crosslinking the rubber polymers along their length, usually by heat and sulfur as in the common vulcanization process. As crosslink density increases so does material strength and durability, but stretchiness and softness decrease at the same time. The rate of crosslinking and the



**Figure 2.** Global climate map, which indicates approximate geographical ranges of the *Hevea* rubber tree, guayule and rubber dandelion.

**Table 1.** A Comparison of Some Properties of the Rubber from Three Species

	Rubber tree	Rubber dandelion	Guayule
Molecular weight	High	High	High
Branching	Yes	Yes	No
Gel	Yes	Yes	No
Protein	High	High	Low
Allergenic protein	Yes	Yes	No
Fatty Acid	Low	Low	High
Tensile Strength	High	High	High
Modulus	High	High	Low
Elongation	Medium	Medium	High

final crosslink density are regulated by the chemical ingredients mixed into the rubber and the temperature and time that the rubber is baked (cured). This is where intrinsic compositional differences really matter because non-rubber components are part of the compound and alter the rubber curing chemistry. Thus, compounding chemistry must be adjusted to fit different natural rubbers from different species.

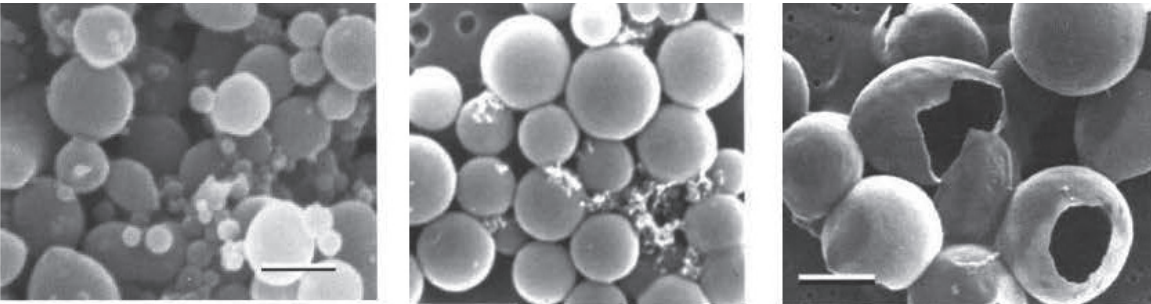
All natural rubber is synthesized and compartmentalized in cytoplasmic rubber particles (Figure 3) (26,27). These rubber particles often are made in multinucleate pipe-like vessels in the bark called laticifers (3). This is the case in *H. brasiliensis* trees and *T. kok-saghyz* roots. However, *P. argentatum* makes its rubber particles in the cytosol of individual bark parenchyma cells (although it does make terpenes in pipe-like resin vessels) (28). The compositional differences of rubber from these species are rooted

in the specific cytosol in which the rubber particles were made (29), the rubber particle mono-layer biomembrane (26), and the extraction method used (tapping, aqueous or solvent extraction).

**NATURAL AND SYNTHETIC RUBBER DIFFERENCES**

SR does not yet exist that can match the key properties of NR. Such properties include high elasticity, high resilience, dynamic performance, high tensile strength, good wear resistance, low electrical conductivity, and excellent heat dispersion. Specific NR properties become progressively more important in tire manufacturing the higher the tire performance required. For example, the rubber component of airplane tires is entirely composed of natural rubber. Compared to NR, SRs are more resistant to oil, certain chemicals, and oxygen; have better aging and weathering characteristics; and demonstrate better resilience over a wider temperature range. Some of these intrinsic drawbacks of NR have been addressed by epoxidized NR in both *H. brasiliensis* (30,31) and *P. argentatum* (32). Epoxidized forms of NR are more oil- and temperature-resistant and have higher hardness, allowing their use in some traditional SR application spaces.

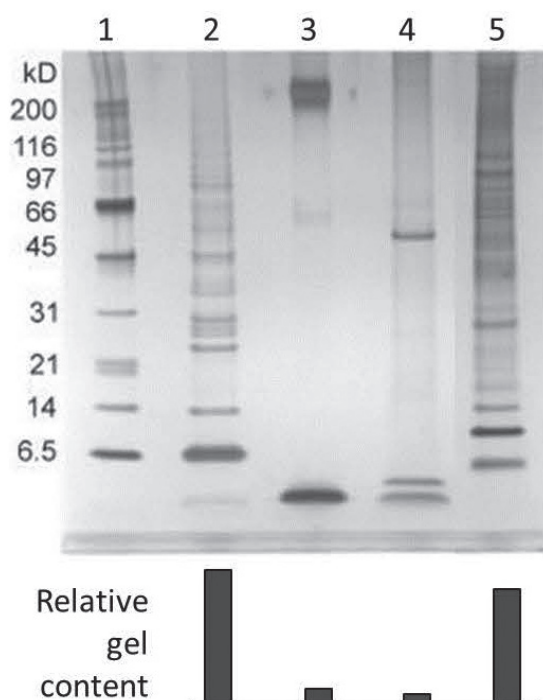
Some major SRs are styrene-butadiene rubber (SBR) produced from copolymerization of styrene and butadiene; butyl rubber (IIR), a copolymer of isobutylene with isoprene; nitrile rubber (NBR), an oil-resistant rubber copolymer of acrylonitrile and butadiene; neoprene (polychloroprene); and *cis*-polyisoprene.



**Figure 3.** Scanning electron micrographs of rubber particles purified from *Hevea brasiliensis*, *Parthenium argentatum* and *Ficus elastica* (from left to right, respectively). The scale bar for *H. brasiliensis* is 1  $\mu$ m and applies to *P. argentatum* as well. The scale bar for *F. elastica* is 2  $\mu$ m.

## NATURAL RUBBER EXTRACTION AND PURIFICATION

*H. brasiliensis* solid rubber is made by tapping the latex from tree bark and then coagulating the rubber by various methods, such as drying or acidification (4). The latex contains rubber particles and all components of the cytoplasm (the nuclei and mitochondria are retained by the laticifer upon tapping so that the laticifer, which is essentially a giant multinucleate cell, remains alive and can resynthesize new latex) (3). Many of these non-rubber cytoplasmic components are retained in the final solid rubber material and become part of the cure compound and finished product (23,24). *T. kok-saghyz* rubber is *not* harvested by tapping root laticifers. Even if this were possible to do, most of the rubber (>75%) in the root laticifers has coagulated *inside* the root during the life of the plant or, at least, at the point of extraction (33,34). This rubber has entrained cytoplasmic components. Also, since there is no apparent value to extracting the <25% latex fraction separately from the coagulated (solid) rubber (35), the harvested roots are dried before extraction, which converts the latex fraction into solid rubber (36). The solid rubber can be extracted either by strong organic solvents (37) or by an aqueous milling (38) and enzymatic process (36). Rubber produced by the aqueous process retains a significant amount of non-rubber constituents, whereas the solvent extraction process can lead to purer rubber. *P. argentatum* rubber also can be extracted by organic solvent from chipped dried shrub, which then requires fractionation to remove resins and degraded rubber (37). However, the rubber particles also can be extracted from fresh shrub in the form of a latex (39,40). Unlike in *T. kok-saghyz* roots, virtually all the rubber in *P. argentatum* bark parenchyma cells remains in the form of individual particles provided the shrub is healthy and hydrated (41,42). Latex extraction requires plant homogenization to rupture the bark parenchyma cells and release the rubber particles into the medium (39,43). The homogenate “soup” contains all components of the shrub and so the particles must be separated from the other constituents. The separation and washing process yields a rubber emulsion (an artificially-produced latex) that contains very few non-rubber particle components, but the particle membrane components are retained and become part of the rubber compound (44).



**Figure 4.** Protein profiles of purified rubber particles purified from different rubber-producing species (top panel) and relative gel content (bottom panel). Lane 1, molecular weight marker; lane 2, *Hevea brasiliensis*; lane 3, *Ficus elastica*; lane 4, *Parthenium argentatum*; lane 5, *Taraxacum kok-saghyz*.

When these different natural rubbers are compared, it is clear that *H. brasiliensis* and *T. kok-saghyz* have similar composition with respect to gel (naturally crosslinked rubber) and protein, while *P. argentatum* has little of either (Figure 4) (20,23,24,29). The membrane is made of protein and lipids, and it is clear that *P. argentatum* has a much higher lipid to protein ratio than the other two. Also, lipid composition is different (29) although we do not yet know the lipid composition of *T. kok-saghyz* rubber particle membranes. The lipid and protein composition of the particle membrane significantly affects rubber particle properties and properties of the rubber itself. For example, the *Ficus elastica* rubber particle lipids are unusually long (waxes), and the proteins are integral to the membrane (29). This makes the membrane stiff (26), and the particles sometimes crack open like little eggs, letting the rubber polymer interior empty out (Figure 3) (27). The waxy membranes and low molecular weight rubber make *F. elastica* dry rubber friable and of poor quality. The proteins and lipids

in *H. brasiliensis*, *P. argentatum*, and *T. kok-saghyz* rubber particles create flexible membranes, and their dry rubber is cohesive and of high quality. The gel component comes in two forms, hard and soft gels, which affect processing parameters. Hard gel does not dissolve in strong organic solvents, whereas soft gels can be rendered soluble by protease and lipase breakdown of intermolecular linkages (45).

## ALTERNATIVE NATURAL RUBBER APPLICATIONS

As discussed above, *T. kok-saghyz* rubber appears similar to *H. brasiliensis* rubber, including in respect to cross-reactivity with life-threatening Type I latex allergy (36). This means that *T. kok-saghyz* rubber shares the same applications as *H. brasiliensis* but certainly will lack the economies of scale needed to compete in the commodity rubber market on price for many years to come. However, it may be possible to interest manufacturers of high-margin products (e.g., shoes, sports equipment, etc.) in premium-priced, “Made in America,” sustainable *T. kok-saghyz* rubber because, unlike tires, such products can absorb large price differentials in their raw materials.

In contrast, *P. argentatum* rubber can capitalize on its intrinsic differences. Performance limitations of *H. brasiliensis* natural rubber latex, currently the highest performance elastomer for dipped products, have been reached in many mature manufacturing industries, including, but not limited to, condoms, weather balloons, catheters, and specialty/medical gloves. However, *P. argentatum*’s rubber is distinctly different, being unbranched high molecular weight rubber with low protein and high fatty acid content. Latex films have superior thin film performance, combining softness and stretchiness with high strength and have *no cross-reactivity with Type I latex allergy* (36,40,44,46,47). *P. argentatum* latex opens up new growth potential to these industries. EnergyEne Inc., an Ohio start-up company focused on guayule latex (GNRL), is targeting initial sales to select specialty high-end products, such as condoms, lineman’s gloves, and high altitude weather balloons, which require the outstanding and unique performance characteristics of GNRL. These relatively small but high added-value markets will also allow revenue to be maximized from initially limited farming and

processing capacity. *P. argentatum* rubber and latex also have better polymer filler interactions than their *H. brasiliensis* versions, which may also prove to supply a competitive advantage to these materials (48,50).

## SCALING UP

In response to transient global shortfalls and/or excessive prices, domestic rubber crops have briefly appeared in the U.S. over the last 100 years but lacked commercial viability in normal economic times. The rubber from both *T. kok-saghyz* and *P. argentatum* can be (and has been) used to produce tires, albeit with distinct compounding chemistries. Early federal and industrial funding mostly supported solvent extraction of *P. argentatum* rubber for the tire industry, as in the Department of Defense’s \$60 million response to the oil embargo of the late 1970s, which drove up rubber prices. However, when rubber prices fell, this investment was not continued, and guayule fell out of favor because of the lack of an immediate need for its rubber. Most recently, Cooper Tire and Rubber Company led a National Institute of Food and Agriculture-Biomass Research and Development Initiative (NIFA-BRDI) 2012 grant for \$6.9 million, and Bridgestone Tire and Rubber Company’s 2014 >\$100 million investment into its Agro-Operations Research Farm (2013) and Biorubber Research Center (2014) has reinvigorated industrial interest. However, security in *P. argentatum* production requires publically available germplasm, established farming practices, and multiple processing companies willing to buy guayule crops from growers and sell purified rubber of consistent quality into the rubber manufacturing industry. Without these connections, farm loans and crop insurance will not be obtainable, and guayule will not be a feasible choice for farmers. Similarly, *T. kok-saghyz* development also is predominately supported by tire manufacturers, especially in Europe, with Continental Tire recently announcing a €35 million investment (2016) for a research facility in Germany and Apollo-Vredestein providing support in a rival effort, but again this is too proprietary, and production is very far from cost-effective. Much more support is needed on the crop development end of both of these alternative crops if they are to fulfill their potential.

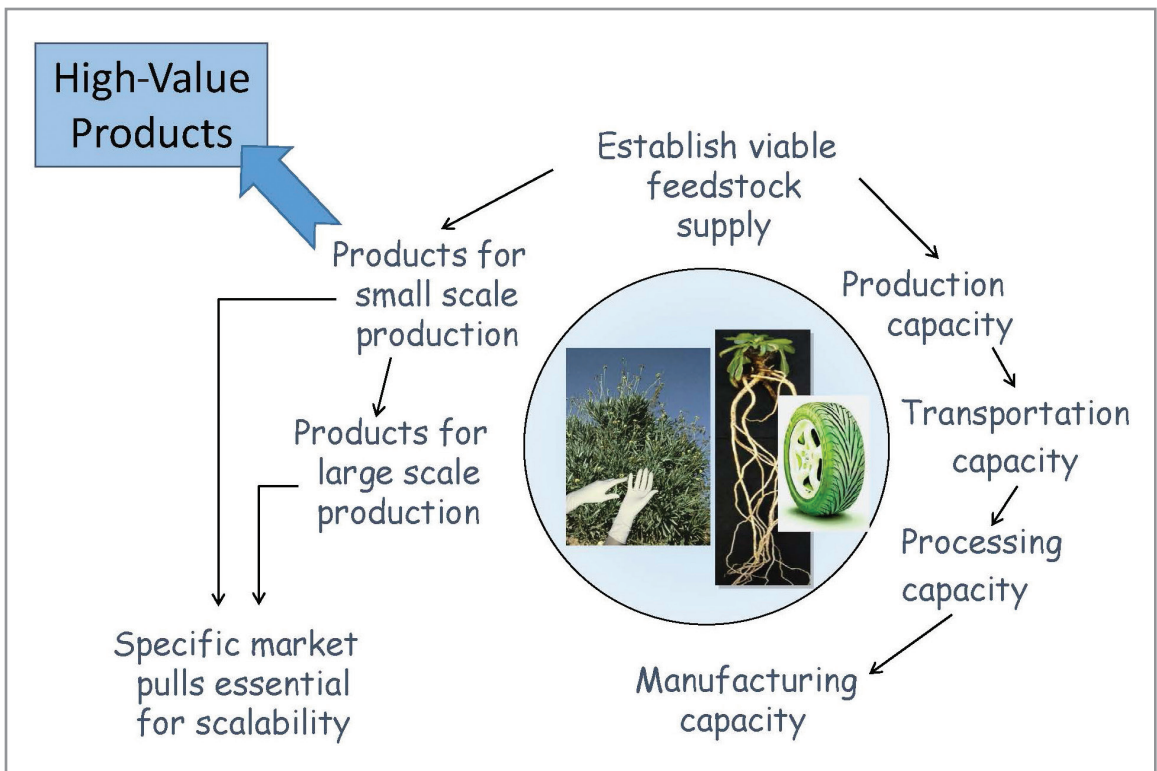
In addition, a major downside of this tire-centric approach is the challenge presented by scaling up these alternative rubber crops. If money is not being made during scale-up, the cost to reach the very large scale suited to commercial tires may be prohibitive (Figure 5). High-value niche applications are absolutely required with concomitant valorization of the non-rubber crop components.

Thus, currently *P. argentatum* remains a perennial crop most suited to aqueous extraction of natural latex (applications are about 10% of the global rubber demand) because it is hypoallergenic (50,51) and produces superior latex films (46). *P. argentatum* rubber is softer than *H. brasiliensis* and is likely to be used only as a minor part of the elastomeric component of most tire types, although 100% guayule tires can be made. However, producing guayule rubber for tires is not a commercially viable path until economies of scale are achieved and enormous production targets are achieved. Tires currently absorb >70% of

the global rubber market, and even a single line of new tires requires capacity well out of the current reach of any alternative rubber crop. Much smaller markets are needed to fund expansion (e.g., shoes, sporting goods, rubber bands, and, in the case of *P. argentatum*, medical and consumer products such as catheters, gloves, balloons, etc.).

## RISK ASSESSMENT

The risks and benefits of *P. argentatum* are reasonably well understood, and no adverse consequences have yet been identified, especially when water-based processes are used. However, *T. kok-saghyz* has a much higher perceived risk because it is a close relative of the common dandelion, a pervasive weed. We are rapidly domesticating this species using classical selection and breeding combined with modern molecular tools. We expect that domestication traits will include changes that may affect the ecological impact of the crop in both positive (e.g., reduced seed



**Figure 5.** Schema illustrating the challenges posed by the imperative to concomitantly scale up crop production and processing capacity and match production to high-value niche markets until economies of scale allow competition in commodity markets.

dispersal) and potentially negative (e.g., increased vigor and herbicide resistance) ways. We are taking care to understand, mitigate, and resolve potentially negative impacts *before* they become a problem for crop production or acceptance (52). We also intend to ensure that farmers, regulators, and the public understand the actual risks of production, instead of the imagined risks, and the proper way to manage the crop to reduce or eliminate the risks. This must be in the context of understanding the economic consequences of not producing this rubber crop. Regulatory bodies attempt to protect the environment, the worker, and the public from negative effects of production, process, and utilization. However, in general, they are understaffed and are generalists rather than specialists. None can be fully informed on any specific new crop or process or material because they need to encounter it first. We need to lead these processes and educate regulatory personnel before they are required to make regulatory decisions. This is a crucial aspect of domestic rubber development across the value chain.

To explain further, *T. kok-saghyz* is a rubber-producing cousin of the obnoxious and pervasive weed, the common dandelion. Commercial fields require excellent weed control to prevent the crop being overwhelmed by vigorous weeds. If we use conventional chemical methods, many questions must be asked: Which ones can be used and at what rates? Do they contaminate the rubber? Do they contaminate the soil? Do they affect the next crop in that field? What is the impact of soil type? And the list goes on. However, it is likely that complete chemical weed control will not be achieved because of the close genetic relationship of the rubber dandelion to weedy dandelion. Genetic herbicide resistance is very probably going to be required. The gut reaction of most people is: “Oh no! This will spread into common dandelion and make it herbicide resistant!” We already have demonstrated that this does not and apparently cannot happen in North America because common dandelion in North America is a triploid obligate apomict, which cannot accept pollen from the diploid, sexual, rubber-producing dandelion. However, we must develop educational tools and wording to explain this to nontechnical audiences in advance of deployment. We also plan to investigate and assess the full ecological ramifications of variants of this new crop, including new hybrid lines with different traits,

which may naturally occur and be found by selection, or are created by mutagenesis or gene-editing (53) by genetic modification (GMO) (54,55), or by interspecific hybridization. In addition, the impacts in North America are not the same as in Europe, and perhaps other growing areas, because Europe is a center of dandelion diversity, and, unlike North America, diploid common dandelions co-exist there with their triploid apomictic form (56) and can readily hybridize with the rubber dandelion. Global interactions need to be explored, understood, and appropriately and sustainably planned for. Another example would be the competition for land between this crop and food crops, which can be investigated and managed in a similar way. There are many more examples related to crop production, of course. However, these broad issues are very difficult for individual researchers to manage.

## THE POLITICS OF ALTERNATIVE NATURAL RUBBER

Extensive interdisciplinary research between academia and industry, supported by a range of funding mechanisms, is clearly required. Competitive grant programs are challenging to put into place because of a general lack of understanding of the strategic and economic importance of NR and the lack of a common frame of reference to inform the need for integrated, informative research from the plant (biologists) through processing (engineers) to the product (chemists).

The Critical Agricultural Materials Act of 1984, Public Law 98-284, recognized that natural rubber is of vital importance to the economy, security, defense, progress, and health of the Nation but did not appropriate funding to address this critical need. However, the economic impacts of successfully deploying alternate rubber crops in the U.S. would be immense. Also, as U.S. alternative rubber crops expand beyond those needed to serve U.S. needs to meet global NR projections, and then to replace part of petroleum-based SR, we predict a mature market supporting at least 50 mt/y NR, on 25 to 50 million hectares, with biofuel production equivalent to ~24 EJ/y. **This is a quarter of today's U.S. energy requirement.** This acreage is 62.5-fold the acreage needed for U.S. natural rubber self-sufficiency and is 2.0-fold the EISA 2007 liquid fuel goal for 2022. Every 20,000 ha of production

would require a processing plant and approximately 4,000 workers across production and processing. As the crop expands, the concomitant infrastructure, rural development, and jobs creation would be enormous (160,000 jobs for U.S. NR self-sufficiency alone, and 10 million jobs to meet global demand).

We have the capability and land area to actually accomplish this. *P. argentatum* can be planted on semi-arid lands, requires minimal maintenance, and the latex in new plantings can be first harvested in only 18 months. Unlike most crops, the shrubs can be harvested throughout the year, and stumps regrow rubber-containing branches, which can be harvested again annually, a cycle that can be repeated several times. Cultivation will not, therefore, directly compete with food production, with the possible exception of beef cattle. The Emergency Rubber Project of World War II estimated a *P. argentatum*-eligible land area of 52 million ha, and much of this land is not currently under cultivation (57) because it is semi-arid. Arizona, for example, has approximately 4 million ha of arable land, and only 0.5 million ha is under cultivation (USDA- National Agricultural Statistics Service, 2016). *T. kok-saghyz* can be farmed on a much larger land area across the northern U.S. This crop is likely to do well on marginal lands, but even on conventional farms, it will have minimal impact on food production if it is incorporated into a validated crop rotation scheme. However, at current rubber prices, 100% crop consumption will be required with development of a multitude of applications to support scaling up (such as resin and biomass derivatives in *P. argentatum* and inulin and biomass derivatives in *T. kok-saghyz*).

If the U.S. is serious about redirecting industrial progress towards the bioeconomy and protecting critical raw materials supplies, it is essential that policy makers are educated and encouraged to support new industrial crops and bio-based materials and products. This is most important at the federal level because, with the sole exception of the United States Department of Agriculture's (USDA) NIFA-BRDI program and the USDA Agricultural Research Service, new bio-based product support has been focused entirely on existing materials produced on a large scale (corn, soybeans, etc.). This past year (2016) is the first time grant programs are combining

bioenergy with bioproduct, which may give alternative rubber crops an opportunity among the many oilseeds competitors looking to elbow into current soybean markets. New specific grant programs are needed because the peer review process in current programs is heavily stacked against new crops, as the peer reviewers usually are not in this field and so do not generally support new crops because they would divert funds away from their own interests. Recent proposals have received occasional good comments on the science but have failed to fund because of views such as "what would corn do if this succeeded?" to the recurrent "I don't believe in new crops—they will never work" to "we can make up the rubber shortfalls with synthetic rubber" (obviously not the case because of performance issues and lack of sustainability).

## CONCLUSIONS

We have a unique opportunity to proactively develop and deploy two major industrial crops with many product applications, as well as the concomitant processing and manufacturing facilities. However, major obstacles impede the accomplishment of this proactively *in advance* of a significant supply shortfall. This proactive approach strongly contrasts with normal reactive responses. In the past, funding has only been released *after* unforeseen problems across the production and value chains have occurred. This time, we can foresee the impending problems in time to address them if "we" so choose.

It is very clear that members of the general public, and sometimes policy-makers, commonly form their views from what they see/hear on mass media—especially television and the internet. Scientists are not very effective at countering erroneous information, and the nation has frequently paid a heavy price for this. Domestic rubber production can demonstrate how effective accurate dissemination of scientific information to the public can be across the entire sustainable materials production chain and is almost as exciting an opportunity as domestic rubber itself. It may even be possible to then use similar approaches to reverse the negative impressions around biotechnological approaches to food crop improvement—a stigma bizarrely not shared by biotechnologically-produced medicines.

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