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Foundations and developments of pest management in Uruguay

a review of the lessons and challenges

Cimientos y desarrollo del manejo de plagas en Uruguay

una revisión de las lecciones y los desafíos

Fundamentos e desenvolvimento do manejo de pragas no Uruguai

uma revisão das lições e desafios

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Abstract

FAO has proclaimed 2020 as the “International Year of Plant Health”. In this context, the present review aims to synthesize the rich history of pest management in Uruguay. To our knowledge, this effort is unprecedented. To accomplish this, the development of pest management methods was compiled from the second half of the 19th century to the present; including changes in thinking and acting on the matter. Milestones in the use of chemical insecticides, biological and ethological control, agroecology and genetic resistance were emphasized for the different production areas (horticulture, fruticulture, intensive cropping, and forestry). In Uruguay, plant health has been present in concerns and actions from the early times. Pioneering in South America due to its early focus on ecological content (e.g. biological control), and a strong relationship between the scientific community (teaching, research, extension), innovative farmers, and the State. Despite of these, it has not been possible to substantially modify the universe of pest control in the country, where the inadequate management of chemical insecticides predominates. However, the growing concern of consumers for safe food, produced in care of the environment (sustainability), transforms this demand into attributes of differentiation and valorization. New milestones are expected to help improve Uruguay's international insertion as a producer of high-quality food, under parameters of social and environmental protection.

Keywords: historical review, pest management, horticulture, fruticulture, intensive cropping, forestry

Resumen

La FAO ha proclamado el 2020 como el «Año Internacional de la Sanidad Vegetal». En ese marco, la presente revisión tiene como objetivo sintetizar la rica historia del manejo de plagas en Uruguay. A nuestro entender, este esfuerzo es inédito. Para ello, se compila el desarrollo de los métodos de manejo de plagas desde la segunda mitad del siglo XIX hasta el presente, con los cambios en el pensar y actuar en la materia. Se destacan los hitos en la utilización de los insecticidas químicos, el control biológico y etológico, la agroecología y la resistencia genética, en las distintas áreas de producción (horticultura, fruticultura, grandes cultivos, forestación). En Uruguay, la temática de la sanidad vegetal ha estado presente en las preocupaciones y acciones desde los orígenes. Con un enfoque pionero en América del Sur de fuerte contenido ecológico (ej. control biológico) y una relación fuerte entre la comunidad científica (enseñanza, investigación, extensión), los agricultores innovadores y el Estado. No obstante, no se ha logrado modificar en forma sustancial el universo del control de plagas en el país, donde mayoritariamente predomina un manejo inadecuado de los insecticidas químicos. Sin embargo, la creciente preocupación de los consumidores por alimentos inocuos y producidos cuidando el ambiente (sustentabilidad) transforma esta demanda en atributos de diferenciación y valorización. Son de esperar nuevos hitos que contribuyan a mejorar la inserción internacional de Uruguay como productor de alimentos de alta calidad, bajo parámetros de protección social y ambiental.

Palabras clave: reseña histórica, manejo de plagas, horticultura, fruticultura, grandes cultivos, forestación

Resumo

A FAO proclamou 2020 como o “Ano Internacional da Fitossanidade”. Nesse contexto, a presente revisão tem como objetivo sintetizar a rica história do manejo de pragas no Uruguai. Ao nosso entender, esse esforço é inédito. Para isso, é compilado o desenvolvimento de métodos de manejo de pragas a partir da segunda metade do século XIX até os dias atuais, com mudanças no pensamento e no agir sobre o assunto. Se destacam os marcos no uso de inseticidas químicos, controle biológico e comportamental, agroecologia e resistência genética nas diferentes áreas de produção (horticultura, fruticultura, grandes culturas, silvicultura). No Uruguai, o tema fitossanidade está presente em preocupações e ações desde o início. Com uma abordagem pioneira na América do Sul com forte conteúdo ecológico (ex: controle biológico) e um forte relacionamento entre a comunidade científica (ensino, pesquisa, extensão), agricultores inovadores e o Estado. Porém, não foi possível modificar substancialmente o universo do controle de pragas no país, onde predomina o manejo inadequado de inseticidas químicos. No entanto, a crescente preocupação dos consumidores por alimentos seguros produzidos com o cuidado do meio ambiente (sustentabilidade) transforma essa demanda em atributos de diferenciação e valorização. Espera-se que novos marcos ajudem a melhorar a inserção internacional do Uruguai como produtor de alimentos de alta qualidade, dentro de parâmetros de proteção social e ambiental.

Palavras-chave: revisão histórica, manejo de pragas, horticultura, fruticultura, grandes culturas, silvicultura

1. Introduction

The Food and Agriculture Organization of the United Nations (FAO) has proclaimed 2020 as the "International Year of Plant Health (IYV)". Commemorating this milestone, we have embarked on this review and reflection with the main objective of synthesizing the rich history of pest management in our country, a pioneer in the region since the beginning of agriculture. To our knowledge, this is the first work of its kind in Uruguay.

Due to the rich history and events related to the subject, the present article is organized in sub-sections, with the objective of highlighting the historical marks in pest management in Uruguay. We begin with a brief review of the initial development of agriculture, and the onset of plant protection against pests in Uruguay (sections 2 and 3). Continuing with the incorporation of synthetic insecticides (section 4), and biological, ethological and genetic pest management programs (sections 5-7). Moreover, the most important milestones for each production system are highlighted (section 8.1 fruit and horticulture, 8.2 organic/agroecology, 8.3 pastures and crops, 8.4 forestry), along with the contributions of the Faculty of Agronomy in the teaching and training of human resources on the subject (section 9). We conclude by providing a summary of the milestones in pest management in Uruguay (section 10), with reflections that emphasize the lessons and upcoming challenges in the area (section 11).

2. The onset of agriculture in Uruguay

Agriculture, as knowledge and practices, already existed in colonial times in the territory that would give rise to Uruguay. In the second half of the 19th century, European immigration gave an indisputable boost to its progress (as an indicator, the existence of 2,506 farmers in the department of Canelones in 1860)[(1)]. Likewise, the "industrial revolution" in Western Europe and the United States generated a growing demand for raw materials and food for these industries. These resulted in profound changes in countries like Uruguay, that underwent "modernization" processes promoted by the government[(2)]. Consequently, the agricultural area in Uruguay was expanded and diversified, with significant increases of both industrial crops (mainly flax) and intensive crops (vineyards, fruit growing and horticulture)[(3)]. Thus, the introduction of new plants and varieties enriched the nutritional diet of the population; which was projected on various industrial activities that were developed from their raw materials (e.g. tobacco, textile fibers, among others).

At the beginning of the 1890s, 280,000 hectares of land were cultivated, increasing to 474,000 in 1900, 836,000 in 1908, and reaching almost 1 million hectares in 1913 (50% of the annual arable land surface)[(3)(4)(5)]. Several factors were the drivers, among them: population growth, the gradual modification of eating habits due to immigration (higher consumption of cereals, vegetables and fruits), the rise of international and domestic prices of cereals, as well as the protectionism to the activity during the Batllista government. The public and private interest in promoting agricultural development in Uruguay co-occurred with the increasing interest on exporting livestock production, which required good land for cattle fattening, and the installation of slaughterhouses. This facilitated the insertion of Uruguay in the world meat market. As a result, tillage areas further away from Montevideo were incorporated[(3)].

Horticulture, fruticulture, viticulture and the cultivation of tubers were the intensive crops of the time. Consequently, in the first decades of the 20th century, the cultivated area and the number of vineyards doubled, and grape harvest tripled, mainly due to increasing demands for imported wines. Likewise, fruit production progressively increased and diversified, decreasing the cultivation of traditional fruits (e.g. peach), but incorporating other species such as apple, pear, among others[(3)]. However, with the aim of increasing production, there was continuous entry of plant material from abroad (imported plants and shoot), frequently through legal channels, and sometimes through smuggling. Herewith, the arrival of exotic insect pest to the country, such as the vine phyloxera (*Viteus (=Daktulosphaira) vitifoliae* (Fitch))[(2)(6)].

Similarly, the presence of exotic forest plants in our territory begins with the first settlers[(7)]. Initially for aesthetic purposes, and later, convoyed by productive activities (livestock), as shade and shelter. In 1853 and 1871 eucalyptus (particularly *Eucalyptus globulus* Labill.) and pine (*Pinus radiata* D. Don Buschenthal) were introduced, respectively. The forest resource, expressed in terms of artificial forests, was scarce and in small forests or "islands", until the explosive increase of its surface takes place in the 1980s.

3. The onset of Uruguay's pest management programs

On March 1st, 1893, the government created a "Phylloxera Commission"[(6)]; resulting on the first insect management milestone in Uruguay. The first detection of phylloxera in our territory dates back to 1888, in vineyards in Salto, with plants proceeding from Río Negro, Argentina[(8)]. Delegates of the commission included scientists trained abroad, along with vineyard technicians. In collaborative efforts with Argentine research centres, the presence of the pest in various areas of the country was confirmed (including Montevideo), and vineyard owners were forced to destroy the phylloxera spots once confirmed. The initial monitoring was difficult, since the owners of the vineyards saw it as a violation of property rights, an intrusion of the country's authority, and an attack on private initiatives. However, the severity of the problem led to the acceptance of the measure and extensive eradications of grapevines[(6)].

The next milestone was in 1907 with the foundation of the Faculty of Agronomy. In addition to training human resources, these institution initiated early (1908) research on pest control (e.g. locusts)[(9)]. Later, in 1911, the "Honorary Central Commission and Technical Directorate of Agricultural Defense" was created by initiative of doctor Eduardo Acevedo, Minister of Industry and Commerce during the second presidency of José Batlle y Ordóñez, initially directed by Roberto Sundberg, one of the first graduates of the Faculty of Agronomy. This organism would later become the National Institute of Agronomy. By law, this organism was confined to the "custody of national agriculture", proposing "to initiate a rational and continuous fight against all the pests of agriculture". Its scope was the entire national territory, by means of rented personnel destined to monitor (with free entry into the properties), perform "agronomic propaganda", and cooperate with owners, tenants, etc., that did not fulfill "their obligation to fight and destroy pests" by means of fines. Only in "cases of notorious and justified poverty" expenses were justified. Moreover, the Institute's powers included the regulation of the introduction of germplasm, fertilizers, products or machinery destined to the extinction of pests into de country. Therefore, by imposing conditions for the introduction of vegetables and other products that could bring harmful organisms to agriculture, this body established the bases for a quarantine system. Likewise, through Article 3 of the regulation, the Commission was empowered to declare as pest any organism that had the probability of "spreading with a calamitous character", and to raise mechanisms for its control[(10)]. In this context, ~30 insects were declared "insect enemies of crops". For each insect, control measures including cultural practices (mechanical destruction or by fire), capture techniques (e.g. trap lamps), and dusting or spraying recommendations, establishing "insecticidal formulas" were published (Table 1)[11]. The State Insurance Bank (since 1914), known as the "Labrador Almanac", became the means of disseminating the law of the Agricultural Defense, it's regulation, along with the "recipes" for pest control[12][13][14][15].

Table 1. Insecticide formulas — Honorary Central Commission and Technical Directorate of Agricultural Defense[11]

Insect *	**Control measure**
Wasps, *Eriosoma lanigerum*	Alcohol
Pieris spp.	Hot water at 45ºC
Epicauta adspersa, *Eriosoma lanigerum*	Potassium soap
Pseudaulacaspis pentagona	Oli
Caliroa cerasi	Freshly slaked lime
Diloboderus abderus	Superphosphate and lime
Ants	Mixture of arsenic and sulfur
Weevils	Carbon benzosulfide
Tinea	Carbon sulfide
Pseudaulacaspis pentagona	Lime sulfide
Saissetia oleae	Soda sulfide
Phylloxera	Carbon sulfide injections
Eriophyes vitis	Sulfur
Planococcus ficcus	Sulfur and iron sulfate
Sassetia oleae, *Lepidosaphes beckii*, *Eriosoma lanigerum*	Tar preparation with alkalis
Cydia pomonella	Soda arsenate
Cydia pomonella	Lead arsenate
Oiketicus platensis	Bordeaux mixture
Pieris spp.	Nicotinated bordolés broth

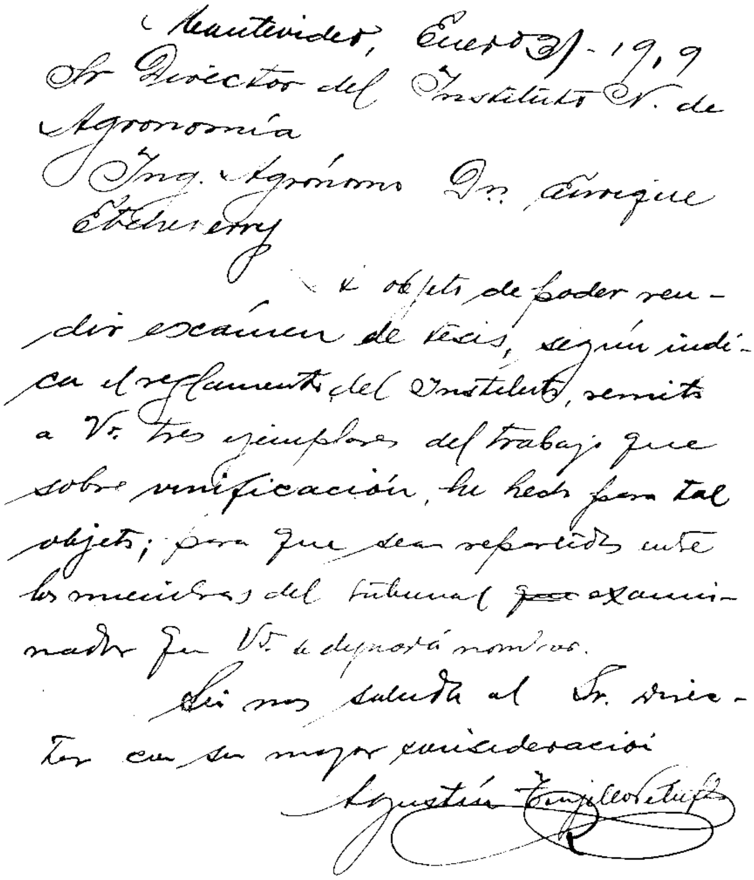
*The scientific names of the insects have been updated and misrepresentations removed

Furthermore, in 1911, the Uruguayan government created "La Estanzuela" National Plant and Seed Institute, under the direction of the German technicians Alberto Boerger and Enrique Klein[16]. This institution, under the name of "La Estanzuela" Agronomic Station, prompted the development of phytotechnical studies in South America. Studies on plant genetics and its practical application for the most important agricultural plants in the country, cereals (wheat, corn, oats, barley), oilseeds (flax, sunflower and others) and industrial and forage species were initiated.

Lastly, in 1912, Agustín Trujillo Peluffo and Roberto Sundberg carried out the first natural enemy importation introducing colonies of *Encarsia berlesei* (Howard) from Italy to control the white peach scale *Pseudaulacaspis pentagona* (Targioni-Tozzetti)[17][18], a milestone that would make Uruguay a pioneer in the area of biological control in South America[19]. Agustín Trujillo Peluffo was a renowned Professor of Entomology at the Faculty of Agronomy, author of many books and scientific articles on agricultural pests and their natural enemies between the 20s and 60s. The letter in Figure 1 are Trujillo Peluffo original transcripts (unpublished) addressed to the director of the National Institute of Agronomy referring to the presentation of his degree thesis (1919). It is almost a tribute to this teacher who was a pioneer, written in the style of his time.

The milestones highlighted here set the stage for "pest protection" in Uruguay during the second decade of 1900; having laid the cornerstones for the development of chemical, biological and breeding control methods.

Figure 1. Agustín Trujillo Peluffo original transcripts (unpublished) addressed to the director of the National Institute of Agronomy (1919)


Montevideo, Enero 31 - 1919
Sr Director del Instituto N. de Agronomía
Ing. Agrónomo Dr. Enrique Etcheverry
A objeto de poder rendir examen de tesis, según indica el reglamento del Instituto, remito a Vd. tres ejemplares del trabajo que sobre vinificación, he hecho para tal objeto; para que sean repartidos entre los miembros del tribunal ~~que~~ examinador que Vd. se dignará nombrar.
Sin mas saluda al Sr. Director con su mayor consideración
Agustín Trujillo Peluffo

4. Incorporation of synthetic insecticides

In 1939, Paul Müller confirmed that DDT (organochlorine synthesized for the first time in 1873 by Othmar Zeidler) was an effective intestinal poison against insects; which allowed him to win the Nobel Prize for Medicine in 1948[20]. Consequently, in 1940, international commercialization of synthetic chemical insecticides took place, changing the situation for Uruguay and the world. These indicated what Metcalf[21] called the "optimism Era" under the conception of total eradication, directed both to human disease vectors (e.g. malaria transmitting mosquitoes), and agricultural pests. The low volatility, chemical stability, solubility in lipids and the slow rate of transformation and degradation of DDT and organochlorines were the main reason for their success (also the case of HCH and its gamma isomer lindane discovered in 1942-1943). These properties, consequently, became problematic due to environmental persistence, bio-concentration and bio-magnification in the food chain. In 1962, Rachel Carson, in her book *Silent Spring* focused world scientific and public attention on these problems, particularly with regard to DDT and related substances. Carson appraised that these molecules particularly affected bird's reproduction. Despite the fierce campaign by the chemical industry against Carson, in the 1970s, due to these and other findings, restrictions on their use were applied in many countries(22). Her book also prompted the World Health Organization to modify its eradication goals for malaria control in 1976(21).

The above resulted on efforts directed to the rational use of insecticides through their physiological and ecological selectivity, driven by various actors, including agrochemical companies, regulatory authorities, users, and the general public. That is, the differences in toxicity between taxa in the first place, and the modification of operational procedures in order to reduce environmental contamination and protect non-target organisms in the second(23). These concepts led to the beginning of the Integrated Pest Management Era (IPM) in 1976(21). IPM applies various tactics and methods to keep pests below the levels at which they could cause economic damage, while maintaining the integrity of agricultural systems through a minimum use of pesticides, and at maximum dependence on the regulatory mechanisms(24)(25). Other approaches with a more holistic vision in pest management (Holistic Pest Management) that consider the social, economic and environmental environment of farmers have emerged the from IPM(26).

Uruguay was not immune to this process of euphoria and subsequent reflection and prohibition of certain synthetic insecticides. In 1945, the insecticidal effect of lindane (gamexane) was pointed out as "one of the most transcendental revelations, if the numerous difficulties opposed to progress and civilization are measured by the destructive action of insects pests that threaten the health and life of man"(27). References indicate that in the 1950s, synthetic insecticides were recommended in Uruguay combined with: botanical insecticides (e.g. tobacco extract, nicotine sulfate, rotenone, pyrethrin), arsenates (lead, calcium, aluminum, copper) or minerals (lime sulfide, polysulfides, emulsifiable oils)(28); belonging to the so-called first generation of insecticides. For instance, the use of chlorinated insecticides (e.g. DDT, lindane, toxafen, chlordane, aldrin and dieldrin) in conjunction with pyrethrums, rotenones or oils, was recommended against domestic pests (flies, ants, fleas etc.)(29). Likewise, products such as dieldrin, HCH, chloradane, DDT, malathion and folidol were recommended against agricultural pests(30). Being the last two products (organophosphates) part of the "second generation of insecticides", together with the organochlorides, which would be followed by the carbamates. Phosphates and carbamates did not cause the accumulation and bio-magnification effects that their chlorinated predecessors had, but being neurotoxic in their mode of action they affected mammals, among them, humans.

In the 1970-1980s, the "third generation" of insecticides, which included pyrethroids, were launched to the Uruguayan market. They meant a renewal of active ingredients of the previous "generation", since some had lost their effectiveness due to massive use. These generation had low toxicity against mammals, but with a risk for non-target (beneficial) invertebrates and fish; due to their wide spectrum of action. Due to their high contact activity, they were effective tools for the control of lepidopteran larvae; molecules 100 times more active than DDT. Likewise, due to their low toxicity, they become useful molecules for public health and industrial environments (grain and food storage). The efficacy of this group was threatened in the long term by pests rapid development of resistance(23)(31). The first registration of a pyrethroids in Uruguay took place in 1979 (fenvalerate), followed by other molecules (e.g., deltamethrin, permethrin, cypermethrin). The use of pyrethroids had great impacts on the control of some pests, for example, *Tuta absoluta* (Meyrick), in tomato cultivation in 1977(32).

The arrival of the "fourth generation" of insecticides, known as *biorracionales*, was also a milestone. This generation has high specificity and, therefore, low toxicity for non-target organisms. They are used in very low doses and have low environmental persistence. They include products based on toxins from microorganisms, such as bacteria (*Bacillus thuringiensis* Berliner), fungi (*Nosema locustae* Canning) and viruses (*Carpovirusine*), and products that alter behavior (e.g., semiochemicals) or regulate growth (juvenile hormone analogues, ecdisoids, and chitin synthesis inhibitors)[23][33][34]. In 1987, methoprene was registered in the Ministry of Livestock, Agriculture and Fisheries (MGAP), being the first growth regulators used in Uruguay. Later, the insecticides triflumuron, buproferin, diflubenzuron, piriproxifeno, among others, were registered (some of them still used today). Other chemical groups incorporated in Uruguay belong to the avermectinas group (first registration in 1982), spinosads (first registration in 1999-spinosad)[35] and anthranilic diamides (e.g. chlorantranili-prole). Subsequently, in 2003, Neonicotinoids (first registry-imidacloprid), widely used today (e.g., thiamethoxam), were registered for the first time in the country. Due to their broad spectrum and prolonged residual effect, they represent, worldwide, the fastest growing class of insecticides[36]. Currently, both in Uruguay and in the world, they are being questioned for their possible connection to the "colony collapse disorder" in honeybees.

Information on insecticides registered with the General Directorate of Agricultural Services (DGSA-MGAP) (Decree 149 of 1977)[37] proves that from 1977 to 1980 there was pre-dominance of products belonging to the "second generation" of insecticides (phosphorous 40%, chlorinated 33.8%, carbamates 5.2%), and an incipient presence of insecticides of the "third generation" (pyrethroids 3.8%). Presently (August 2020), a strong reduction in insecticides of the "second generation" (phosphorous 12.7%, carbamates 3.8%) and a high presence of insecticides of both "third generation" (pyrethroids 24.8%), as well as growth regulators 15.3%, avermectins 12.1%, neonicotinoids 9.6% and anthranilic diamides 8.3% are reported. Currently, there are no authorized chlorinated insecticides[38]. Likewise, the import figures (cif values in dollars) of insecticides made by the country in 2019 indicate that avermectins represented 41% of the total, followed by 20% anthranilic diamides. However, when it comes to kilograms of active matter, phosphorous insecticides represented 44%, followed by growth regulators in 17%; figures that must be taken with caution because the amount of active material per hectare used in these chemical groups is very different[39].

Various factors influenced the change in the supply and use of chemical insecticides in Uruguay over the years. Among them, the questioned efficacy of molecules used for many years, the successive presence on the market of new chemical groups with different characteristics, and finally, the partial or total restrictions on the use of certain insecticidal molecules established by the Uruguayan government. In this sense, the most significant prohibitions or restrictions include:

a) Chlorinated insecticides formulated based on aldrin, dieldrin, endrin, chlordane, heptachlor, hexachlorocyclohexane gamma isomer, DDT and endosulfan, for the control of pest insects in natural fields and grasslands (implanted and/or cultivated). Except for the use of chlorinated ants for localized treatment of ant hills (1968). Pesticides based on hexaclorocicloexano (HCH), with the exception of the gamma isomer (1977).

b) Pesticides based on endrin, for any agronomic use other than the control birds (1988).

c) Chlorinated insecticides, except for the control of ants with an active ingredient concentration not exceeding 2.5%. With the exception of insecticides formulated based on endosulfan or endrin (1989). Products based on etil parathion, metil parathion, monocrotofos (2002).

d) Methamidophos (2006), endosulfan (2011), azinfos methyl, metidathion, metomil and the restriction in certain cases of carbofuran (2016)[40].

To better visualize the evolution in the use of insecticides in plant production in Uruguay, it is necessary to mention the total volume of imported insecticides. That went (in millions of dollars) from 2.9 in 2000[41] to 19.5 in 2018, with a maximum of 44.9 in 2014[42]. This 700% increase is related to the "intensification" of agriculture that occurred in the last two decades in the country, exemplified by the increase in the area of soybean cultivation. Such culture occupied 9,000 hectares in the 1999-2000 growing season[43], and increased to a maximum of 1,334,000 hectares in 2014-2015[44]; to then begin a decline that placed the area at 966,000 hectares in 2018-2019[45].

Being soybean a summer crop commonly attacked by various pests, its expansion led to the excessive application of insecticides, under the erroneous paradigm of achieving "zero damage". This was complemented by calendar insecticide applications, precautionary application with other phytosanitary products (e.g. herbicides), as well as planned applications due to temporal availability of the application machinery (*mosquitos*) on the property; all these encouraged by the low cost per hectare of many insecticides due to their generic nature. Since several insecticides (mixtures) are applied simultaneously, the benefit provided by new "generations" of insecticides is generally lost. Conversely, more selective chemical insecticides that are part of programs that combine biological and chemical methods in other countries (e.g. Europe) are not registered in Uruguay, due to low demand in our market.

5. Biological control

Biological control methods followed an evolution in Uruguay not alien to what was happening in the world, and the impact of synthetic chemical insecticides. As a highlight, Uruguay was one of the pioneer countries in South America in the implementation of biological pest control initiatives, when in 1913 the parasitoid *E. berlesei* was successfully introduced, from the United States, for the control of *P. pentagona* (after previous failures). Together with the subsequent introduction of the predator *Lindorus lophanthae* (Blaisdell) in 1915, this resulted in the permanent control of this pest in the country[17]. Only Peru had previously registered the importation of the same parasitoid in South America[19].

The difficulties involved in getting biological control agents to Uruguay from Europe or the United States, transported in long boat trips before reaching Montevideo, forced in many cases to strain several attempts. In some occasions, it was also necessary to send officials to the countries of origin, to ensure the survival of natural enemies. Despite this, in the first years of the last century, the entry of *Novius cardinalis* (Mulsant) (1919) and *Aphelinus mali* (Haldemann) (1921) for the control of *Icerya purchasi* (Maskell) and *Eriosoma lanigerum* (Hausmann), respectively, was successful[17]. Hence, effective biological control of the respective pests was achieved[18].

The national success of these programs was due not only to the rapid response of the government to the appearance and spread of exotic pests, but also to the rapid implementation of a short-term strategy (chemical control), with a focus on more-permanent biological control approach (long-term). Uruguay also became an important supplier of biological control agents at that time, re-exporting these exotic species to the southern region of the continent[17].

Although in the course of the last century other cases of successful introductions of natural enemies were reported (see Basso and others[46] for more details), it is in the last decades when this practice has intensified; profoundly to control exotic forest pests. This augmented after the accelerated growth of the forested area in the country starting in 1987 (Law 15,939, known as the "second forest law")[47]. This includes the following natural enemies: *Avetianella longoi* (Siscaro) in 1999, *Psyllaephagus pilosus* (Noyes) in 2001, *Cleruchoides noackae* (Lin and Huber) in 2013, and *Selitrichodes neseri* (Kelly and LaSalle) in 2019. Being classical biological control (introduction) the most appropriate tactic to face the invasion of species in an forestry agroecosystem[48].

Inundative biological control, based on the application of biological insecticides to replace chemical insecticides in horticultural or oilseed crops, also gained importance. For example, based on National Institute of Agricultural Research (INIA) in conjunction with the company Lage y Cía SA, Lecafol was the first biological insecticide formulated in Uruguay based on fungus *Lecanicillium lecanii* (Zimm.) Zare & W for the control of the greenhouses whitefly *Trialeurodes vaporariorum* (Westwood) in tomato cultivation (commercially available from 2013 to 2017)[49]. Alternatively, 500 hectares of sugar cane, since 1988, have been subjected to *Trichogramma galloi* (Zucchi) releases for the control of *Diatraea saccharalis* (Fabricius)[50][51]. Although the sugarcane program was canceled, other *Trichogramma* spp. were evaluated for their use with grapevines[52], apples (1998-1999), cotton (1998), and lotus (2001)[53]. Since 2003, releases of *Trichogramma pretiosum* (Riley) have been evaluated in transgenic and non-transgenic soybeans[54]. In 2019-2020 seasons this parasitoid was released in 3,000 commercial soybean hectares, as part of an alliance between the Faculty of Agronomy, Barraca Jorge W. Erro SA, Bioline Agroscience and the support of the National Agency for Research and Innovation (ANII). This initiative seeks to generate an innovative product (non-transgenic soybean with pest control through biological control), capable of being differentiated and valued in markets intended for human consumption.

The development of a microbial control agent based on a baculovirus for the control of *Rachiplusia nu* (Guenèe), the sunflower looper, is also highlighted. This was carried out in the DGSA-MGAP with the support of producers' associations from 1989 to 1997. In this program massive rearing of the lepidopteran and the virus were achieved[55][56]. The formulated biopesticide was first applied to 600 hectares of sunflower using an airplane in 1994[57]. Similar research was conducted for the multiplication of the *Anticarsia gemmatalis* (Hübner) virus. Although the results were promising, the program did not continue.

The recent advance of augmentative biological control at a commercial level has been stimulated by the DGSA-MGAP, and is reflected in a 2007 resolution in which the use of biological control agents was declared of interest for agricultural production[58]. Equally, in 2013, a regulation was approved for the registration of biocontrol products based on microbial control agents[59], and in 2014 another one based on entomophagous[60]. Currently, there are four products available on the market based on entomophagous for bell pepper, tomato and soybean pests: Swirskii System (*Amblyseius swirskii* Athias-Henriot), Orius System (*Orius insidiosus* Say), Tupio System (*Tupiocoris curcubitaceus* Spinola) and Tricholine Maxi (*T. pretiosum*)[38][46]. Bell pepper represents the vegetable for which the most progress was made in terms of biological control, where ~35 hectares are protected annually under greenhouse (20-25% of total area)[44]. These initiatives were possible with the support of the Faculty of Agronomy, INIA and a private company (Brometan).

Controlled studies on plant-phytophagous-natural enemy interactions carried out at the Entomology Unit of the Faculty of Agronomy determined the low efficiency of one of the released natural enemies and proposed solutions[61][62].

One hundred years after the first importation of a natural enemy, the beginning of the commercial application of biological insecticides took place in the past decade; although still restricted, it greatly marks the development of biological control in Uruguay. This process has been possible thanks to long-standing national research, based on continuous efforts to have an inventory of biological control agents for the most economically significant crop pests[63][64][65][66]. In particular, between 1988 and 1992, INIA and the Faculty of Agronomy strengthened collaborations by conducting surveys both in crops and pastures. Focusing on the most important pest species, such as, *Pseudaletia adultera* (Schaus), *Faronta albilinea* (Hübner)[67] and *Crocidosema (= Epinotia) aporema* (Walsingham)[68][69].

Furthermore, in 2001 the book *Natural enemies: Illustrated manual for agriculture and forestry* was published, being a milestone in biological control research in Uruguay[70]. As a result of this publication, surveys on natural enemies became increasingly frequent. For example, from 2004 to 2007 an inventory of biological control agents (BCA) of *Piezodorus guildinii* (Westwood)[71][72] was carried out, including studies on the behavior and biology of these BCA in relation to their host[73][74]. Additionally, the natural enemy complexes of *A. gemmatalis* and forage legume aphid species were also surveyed (2005-2007)[75][76][77][78].

In 2013, the *Bioinsumos* (bio-inputs) platform based at INIA was created. This platform maintains, collects and receives microbial strains with potential microbes to be used as bio-fertilizers and biocontrol agents for insect pests and diseases[79].

Finally, in 2015, the Faculty of Agronomy, in collaboration with the University of California, in Berkeley (US), evaluated the influence of the landscape (simple or complex) in the communities of beneficial insects in grain sorghum and soybean systems. These studies began with the premise that the Uruguayan agricultural-pastoral systems have great potential for the conservation of natural enemies[80][81].

6. Ethological control

There has been significant advance in the knowledge of insect communication mechanisms presently, which has made it possible to develop specific, safe, effective pest control methods with practically no effects on non-target organisms nor the environment. Through these methods, the behavior of adult insects is disturbed; for example, by communication between the sexes to prevent encounter and subsequent reproduction ("sexual confusion"). Essentially, the environment is overloaded with the female's synthetic sexual pheromone, in order to alter male's behavior. This method also allows mass trapping techniques, that is, the use of semiochemicals for direct control of pest insects (sexual and aggregation pheromones, food attractants, plant volatiles)(24)(82)(83).

In Uruguay, studies on this subject, based at the Faculty of Chemistry in conjunction with the Faculty of Agronomy and INIA, have contributed to the chemical characterization and synthesis of sexual pheromones of various species, including *Argyrotaenia sphaleropa* (Meyrick), *Bonagota cranaodes* (Meyrick), *C. aporema*; the first two in the registration process. Also, other studies of pheromones of insect pests of various crops, including emerging pest of the forestry sector, have been executed. These studies are particularly important when they include pest species restricted only to this region of the world(84)(85)(86)(87)(88)(89).

7. Genetic management

The resistance of plants to insects is achieved through mechanisms that prevent colonization by insects (antixenosis), their growth and reproduction (antibiosis), or that stimulate plant characteristics in a way that does not be affect insect feeding (tolerance). These mechanisms can appear separately, together, or in different proportions(90).

The use of genetic material resistant to insects has distant origin examples in Uruguay, starting with the use of rootstocks in vine and apple crops. In the first crop, between 1893 and 1903, there was massive introductions of rootstocks, mainly *Vitis riparia* and *Vitis rupestris*, along with hybrids, as a response to the phylloxera crisis(8). However, the high costs of replanting vineyards demanded by this measure had serious social consequences due to the disappearance of many viticulture producers. This same situation had previously happened in Europe, causing the emigration of impoverished producers to our continent(2). However, in 1977, rootstocks with SO4 sanitized material (*Vitis berlandieri x Vitis riparia* cross), resistant to both nematodes (*Meloidogyne* sp.) and phylloxera(91), were introduced to the country. Currently 63.1% of the vineyard area of Uruguay utilizes these rootstocks(92).

In apples, the resistance or susceptibility to the "woolly apple aphid" integrates one of the characteristics evaluated in the rootstock improvement programs. Such concern dates back to the first half of the last century, when the introduction of the parasitoid *A. mali* and less susceptible apple varieties that serve as rootstocks were the tools to control this pest that conditioned the existence of apple cultivation in our country(28). Work carried out in England in 1922 and 1924 by John Innes resulted in a number of clonal rootstocks with varied resistance to this pest, which have been progressively available in Uruguay(93).

Since its foundation, La Estanzuela Experimental Station has pioneered research on genetic resistance of crops to pests(94). In the forage grasses, the selection of ryegrass *vr 284* stands out as the first reported case of a variety resistant to the greenbug, *Schizaphis graminum* (Rondani), as well as to *Puccinia coronata,* the latter being a disease.

Based on the three aforementioned components, in 2010 the resistance mechanisms against aphids were characterized in perennial forage legumes. Focusing on species of economic importance; spotted (*Therioaphis trifolii* Monell), blue (*Acyrthosiphon kondoi* Shinji), green (*Acyrthosiphon pisum* Harris) and black (*Aphis craccivora* Koch) aphids. These species cause direct damage to forage legumes, and are vectors of viruses that reduce plant productivity and survival(95). Likewise, resistance to greenbug, *S. graminum*, was characterized in a collection of native populations of yellow oats. This work was very important because the susceptibility of oat materials to aphids compromises the establishment of the crop, and, consequently, the production of forage[96].

Genetically modified crops are another tool that has been developed in the world to control pests. In Uruguay, in 2003, MON810 corn with toxicity to certain lepidopteran larvae was approved. Toxicity derives from the insertion of transgenes from the *B. thuringiensis* bacteria in these plants, and the subsequent production of proteins (Bt toxins), that confers resistance to insects. MON810 was followed by other simple and stacked events that produce Bt toxins (RI) and/or show tolerance to glyphosate (TH) and/or gluammonium phosinate (GA)[97]. Bt corn reached 100% adoption in 2017, including: 96% RI/TH corn and 4% TH corn[98]. Zerbino[99] published a report on the “impact of the use of Bt maize in the communities of pest and beneficial insects”, with results that infer the efficacy of transgenic crops against pests of economic importance (e.g. *Spodoptera frugiperda* Smith), and highlights that the number of predators per plant in genetically modified cultivars and refuge (non-transgenic) were similar. However, the incidence of parasite was lower in transgenic crops.

In soybean, the first Bt event with toxicity to Lepidoptera larvae (IR) was approved in 2012 (MON89788 x MON87701 BPS-CV127-9, Intacta RR2 Pro). This event is complemented with tolerance to TH, which first entry was approved in 1996 (Roundup Ready-RR)[97]. In 2017, the adoption of transgenic soybeans reached 98% of the total area, were 74.4% corresponded to TH soybeans, and the remaining 25.6% to IR/TH soybeans[98]. Currently, there is ongoing debate on the real effect of Bt events for the main pests of these crops in Uruguay.

8. Pest management milestones in different production systems

8.1. Fruit and horticultural production

The concern to make good use of chemical insecticides found fertile ground in fruit production in Uruguay, due to the fact that, traditionally, to protect the commercial product (the fruit), repeated treatments were carried out with a calendar-based application program. Thus, in the 1950s, forecast systems for lepidopteran pest of deciduous fruit trees began to be implemented in Uruguay by the Regional Agronomy Directorates of the MGAP. Consequently, the creation of the Las Brujas Experimental Station (INIA) implemented this system towards the end of the 1970s, reducing the number of insecticide applications in apple trees by 50%. In 1990, the DGSA-MGAP continued with the pest alert service in deciduous fruit trees[100]. At the beginning, feeding traps (Diamalta 5%) were used and, from 1975, pheromone traps for *C. pomonella* and *Grapholita molesta* (Busck.)[101] were incorporated. In 1979, this information was complemented with temperature records for the calculations of degree day models[102][103].

In 1989, the Entomology Unit of the Faculty of Agronomy and INIA Las Brujas began evaluations on sexual confusion pheromones for the control of *G. molesta*[104][105]. Later, these studies were also extended to *C. pomonella*, which allowed continuing the successful application of the method against these two pests at commercial establishments level.

In 1997, the Integrated Production (IP) program started, founded by the German Technical Cooperation Agency (GTZ), the Faculty of Agronomy, INIA, the National Farm Board (now DIGEGRA), and fruit and horticultural producers. Subsequently the producers created their respective associations (AFRUPI and AHPI). Cooperation with GTZ was extended until 2003 inclusive. The Program proposed the development of a production management system that goes beyond plant health, using biological, cultural and chemical techniques. Thus, minimizing the undesired effects of agrochemicals on the environment, and maximizing the health of rural workers and consumers. IP standards were developed for plums, peaches, apples, pears, table grapes, garlic, sweet potato, onion, strawberry, lettuce, sweet corn, melon, bell pepper, potato, cucumber, tomato (industry and table), carrots, squash and zucchini, among others[106][107][108][109]. This task continues with periodic reviews, and the process was accompanied by the corresponding certification, reflected in the commercialization of the products arising from IP, a situation that has not reached a significant level in most of the areas involved, and that has reduced its impact at the fruit and vegetable market.

At the legislative level, the MGAP in 2002 promulgated Decree No. 143/002 on the “Regulation of Integrated Production of fruits and vegetables”, which established the conditions for the trade of fruit and vegetable products under the name of Integrated Production[(110)]. This was updated in 2019 (“General Directives for Integrated Fruit Production”, in charge of the Coordinating Committee for Integrated Production), through resolution 291/019 of the DGSA-MGAP[(111)].

With an inter-institutional character (Faculty of Agronomy, INIA, DIGEGRA, DGSA) and the participation of producer groups, various research, training and promotion activities have continued through the development of projects under the Techno Promotion Fund (FPTA), focused on the main horticultural and fruit crops. Unfortunately, the correct use of insecticides is far from being achieved in a generalized way.

During the 2010-2012 growing seasons, a plan was carried out on 300 hectares of pome and stone fruits with the participation of the JUMECAL cooperative (*Juventud Melilla Cooperativa Agraria Responsabilidad Limitada*, Melilla, Montevideo), applying the wide area approach. In 2012, this program reached regional dimensions with the support of DIGEGRA, which allowed it to cover 3,563 hectares two years later; almost 85% of the commercial fruit production area. This involved 360 growers and nearly 70 scouts, who assessed field damage, followed insect populations using pheromone traps, and recorded pesticide applications. The results showed less than 0.5% pest damage, and a reduction in the use of insecticides was recorded for more than 95% of the area covered by the program[(112)]. The program continues today, comprising a total of 3,473 hectares and 405 producers in the 2018-2019 season (information provided by the JUMECAL cooperative).

Consequently, in the last decade an initiative began, aligned with the international trend promoted by the Global GAP to define “Good agricultural practices”[(113)]. As a result, a guide on the production of fresh fruits and vegetables was approved in 2014 by resolution 1050/014 of the MGAP[(114)]. This guide, according to the authors, was developed in response to the changes registered in the fruit and vegetable trade where demands of sustainability criteria were added; in order to provide a differential value to the products, and a “floor” on which to settle other production systems, such as Integrated Production. This initiative is still in the adoption stage by the producers.

Regarding citrus crops, the first report of insect pest is referenced in 1913[(11)], when *Saissetia oleae* (Olivier) is included among the main pests, and soda sulfide is proposed for its control (Table 1). Later, in the 1940s, alkaline polysulfide was recommended in winter, and emulsifiable oils in spring to control scales[(28)]. These latter products have remained the most widely used in the subsequent years, in some cases combined with synthetic chemical insecticides. The importance of the item has led to research on scales and other pests (drills, thrips, mites, aphids, whiteflies), with inventories, biological studies and control tests[(115)(116)(117)(118)(119)].

In 1997, *Phyllocnistis citrella* (Stainton) was detected for the first time in Uruguay. *Phyllocnistis citrella* is the only important lepidopteran. Joint studies between the Faculty of Agronomy and INIA (Salto Grande Research Station) allowed extensive knowledge about its biology, ecology and control methods[(120)]. Within this framework, in 2000 the parasite *Ageniaspis citricola* (Logvinovskaya) was introduced from Argentina[(121)]. Additionally, *Citrostichus phyllocnistoides* (Narayanan) was introduced in 2004 from Argentina, and in 2005 from Spain, massively produced and released until 2006. Established *A. citricola* populations can be found in Uruguay annually, mostly during fall months (April-June), but *C. phyllocnistoides* is rarely found in the field. The control efficiency of these two species has not yet been evaluated.

Presently, *Diaphorina citri* (Kuwayama) represents the greatest concern in citrus. This pest, detected in Uruguay in 1991[(122)], is a vector of the bacteria that cause Huanglongbing, the most destructive citrus disease in the world today. This disease has not been detected in the country; nevertheless, it has been detected in the region, placing the Uruguayan citrus industry in a high-risk situation. There have been many biological, ecological and control studies on this pest[(123)(124)(125)], and in 2016 *Tamarixia radiata* (Waterston) was introduced from Mexico. After successful mass rearing, the first pilot release was carried out during the summer (January-March) of 2017. A project was funded by the ANII since 2019, on a partnership with MGAP and the main companies in the citrus production organized in the UPEFRUY association. The main aim is to develop a technology for mass production of *T. radiata* and control experiences.

Another topic that has attracted interest in researchers for many years is "fruit flies". Thus, the United States prohibited the entry of Spanish grapes due to the presence of *Ceratitis capitata* (Wiedemann) in 1923. This circumstance led Agustín Trujillo Peluffo to move two years later to Brazil (where this insect was present) in order to carry out a training internship on this pest, before its invasion in Uruguay. This presumption was realized in 1927; ten years later it was declared a national pest. In 1948, the parasitoid *Tetrastrichus giffardianus* (Sivestre) was introduced from Brazil, but did not prosper due to the winter conditions in Uruguay. Another "fruit fly" reported from the same origin was *Anastrepha fraterculus* (Wiedemann)(17). Traditionally, for control measures, the recommendations have included the use of toxic baited traps (*mosqueros*), and spraying some of the plants with sugary and toxic substances to attract and kill the flies. Insecticidal substances have varied; such as sodium fluosilicate and beet mix prior to synthetic insecticides(28). Since late 1950s, the most commonly used toxicant in bait sprays has been the organophosphate insecticide malathion, and the most popular protein bait NuLure. However, organophosphate insecticides have been restricted due to their negative effect, which is why they have been replaced by others of lower risk, such as spinosad(126).

Recently, the requirements of citrus-fruit-importing countries have led to the development of a "Phytosanitary Certification System" that ensures the traceability of shipments, and enables advance knowledge of the phytosanitary situation at the origin(127). Within this framework, in Uruguay the DGSA-MGAP has been running since 2001 a National Monitoring System for fruit flies in citrus crops(128), and more recently in blueberries. Traps with sexual attractants are used to capture *C. capitate*, and with food attractants for *A. fraterculus*. Mass trapping alternatives have been evaluated with promising results, a technique that has been successfully adopted by numerous producers(129). On this subject, two research projects were executed in the 2013-2018 period (María Viñas Fund-ANII and Agricultural Promotion and Technology Fund-INIA). These studies determined the fruit fly species that predominated in different cultivated and wild hosts, their population fluctuation in different areas of the country, the relationship between the levels of capture of adults in traps, and the percentage of damage in fruits, descriptive models and a geographic information system, the evaluation of different attraction baits, as well as their impact on beneficial organisms(126).

8.2. Organic Production and Agroecology

Another area where crop protection techniques have been developed in Uruguay involves the so-called "organic, ecological or biological production". This type of production is oriented to processes, rather than products. It was defined in 2008 by the National Executive Power through decree 557 as "any method of sustainable production over time that, through rational management, preserves natural resources, biological diversity and the environment, without the use of chemical synthesis products or genetically modified organisms or derivatives thereof"(130). Consumers buy products primarily because they perceive the benefits they bring to health, food safety and the environment. As these characteristics are not easily observable in products, their certification is required, which is established in the previously mentioned decree. No progress was made in this System, and there is currently a Participatory Certification Program(131).

Certified by this Program, there are 150 farmers dedicated to the production of vegetables, fruits, and dairy products for the domestic market whose farms' average is of 7 hectares(132)(133). Likewise, there are 1,207,000 hectares of certified organic meat production farms in the country, for export purposes; integrating 400 properties with an average surface of 2,900 hectares. Currently the organic area represents 7% of the national agricultural total(132).

The current reality of organic production is closely linked to the concept of agroecology, which comes hand in hand with the increase in the world interest in promoting sustainable agriculture due to indisputable signs of environmental degradation, uncontrolled economic growth, social marginalization, etc. Gallardo-López and others[133] point out that the beginning of agroecology at the international level can be set in 1928, when this concept was used for the first time by Russian Basil M. Bensin to describe the use of ecological methods in research of commercial crops. According to Gazzano Santos and Gómez Perazzoli[132], in Uruguay the first mention of the term *agroecology* appeared in 1939, in a publication by the Association of Agricultural Engineers of Uruguay[134]. This publication was based on an article by that Russian agronomist, where he called attention to the need for international cooperation in agroecological research, and called the science supporting this research Agroecology[135]. Subsequently, the critical stance to the so-called "green revolution", together with the construction of alternatives, gave rise in the 80s to a series of actions in the field of NGOs, the University of the Republic and movements of farmers. As milestones, we can cite the Conformation of the Agroecology Board (1987) that brought together producers, technicians, consumers and members of NGOs; the Association of Organic Producers of Uruguay (1996); the Network of native seeds (2004); the Uruguayan Agroecology Network (2005), and the Consumer Organization (2015). From this approach, a profound questioning of conventional agriculture is made, and alternative production proposals are offered. During 2015, members of these organizations developed a National Agroecology Plan, which entered the Senate as a bill in 2016 presented by the Executive Power[136]. This was approved by Parliament in December 2018 through Act 19717[137]: "Declaration of general interest and creation of a National Honorary Commission and National Plan for the promotion of production with agroecological bases", and the subsequent approval of its regulation in June 2019. Among other initiatives, in 2005 "the Orchards Program in Educational Centers" was created, which consists of the installation and maintenance of agroecological school gardens with productive and demonstration pedagogical purposes[132].

8.3. Pastures, forage crops, cereals and oilseeds

INIA La Estanzuela and the Experimental Station Mario Cassinoni of the Faculty of Agronomy (EEMAC) have stood out for research, dissemination and, in the latter case, for teaching on the pest management issue in this area. The themes and approaches varied over the decades, influenced by the relative importance of crops and their pests, and the evolution of approaches and control tools.

Pastures, both natural and sown, provide an ideal (stable) environment for a large number of insect species, both phytophagous and natural enemies. In INIA La Estanzuela and the EEMAC's inventories of phytophagous species, their biological control agent complexes, population fluctuation studies, damage estimation, and control tests were investigated[69][138][139]. *Crocidosema aporema*, recognized for its damage mainly to red clover and lotus, had significant attention, which led to numerous studies and publications. In 1989-1991, a monitoring program for this pest in legumes started; based on its findings, in 1992 the entomopathogenic fungus *Zoophthora radicans* (Brefeld) Batko was isolated. It was postulated as a possible biocontrol agent and evaluated as a probable commercial product, being rapidly and easily dispersed through rice grains inoculated in the laboratory[68]. This pest species also acquired relevance in soybeans in the 70s, when morphological and biological studies were carried out[140], and it regained interest after the year 2000, when soybean production increased its plantation area[69][138][139][141].

The greenbug *S. graminum* (Rondani) in sorghum cultivation in the 1980s can also be cited[142]. In that same decade, studies began at INIA La Estanzuela on *Pseudaletia adultera* (Schaus) in wheat, although it attacks other grasses, such as oats, barley, ryegrass, rice, phalaris, corn and grasses of natural pastures. According to data from the Chamber of Agrochemicals, *P. adultera* was the insect which most money was spent on for its control in the country in 1987; its biology was studied, including varietal behavior, level of damage and population dynamics[143].

Additionally, *P. guildinii* egg parasitoids complex was characterized for soybean, the product of a collaboration between the INIA and the Faculty of Agronomy. *Telenomus podisi* (Ash-mead) resulted in the most dominant species[72]. Likewise, a national survey of aphid mortality agents in legumes was conducted, highlighting both different species of BCA, such as the entomopathogenic fungus *Pandora neoaphidis* (Remaudière and Hennebert) as the main agent of mortality[75].

Recently, the dispersion capacity of *P. guildinii* between soybean and alfalfa crops during grain filling was investigated. This study was revolutionary in Uruguay, since the dispersion was characterized by using protein markers (alfalfa = bovine casein, soy = soy protein). Thus, information regarding the unidirectional and bidirectional movement between crops was obtained. This work concluded that movements from soybeans to alfalfa were predominant, so the establishment of sowed strip of alfalfa that remains in fruiting during the reproductive stages of soybeans can be an effective tactic to reduce colonization soybean[144][145]. In another line of work, the transfer of pesticides (neonicotinoids) applied in soybean crops to bee hives was evidenced, which made it possible to locate the hives as quantitative monitors of environmental quality[146].

In 2013, based on an agreement between MGAP, the National Wheat Board, Oilseeds Technological Board, and the National Board of Beer Barley Entities, they approved the “Guide to good agricultural practices, for systems with agricultural rainfed in Uruguay”, which, according to the authors, aims at caring for the environment, the safety and well-being of workers, and obtaining safe products. Pest management recommendations are included, among others, and are aimed at intervening only to reduce pest populations when strictly necessary, knowing, evaluating and respecting natural enemies, planning the system agriculture in order to make the crop less susceptible to pest attack. Thus, periodic samplings to detect the presence of pests and make the decision by analyzing the economic aspects of the crop and the cost-benefit relation of control of pests are required[147].

Also in 2013, the Association of Rice Growers and the Association of Rice Mills with the support of the Faculty of Agronomy, INIA and the Technological Laboratory of Uruguay (LATU) drew up the "Guide to good practices in rice cultivation in Uruguay”. According to the authors, the objective of this Guide is to direct and make available to producers, technicians and workers in the rice sector the recommendations and knowledge available for the sustainable production of rice, in order to guarantee the highest productivity and enhance the competitiveness of the rice sector at national and international level. With regard to pest management, it was recommended to base actions on periodic monitoring of the agents that affect the crop, and decide the actions to take with a detailed knowledge of the chemical products, a correct selection of the application mode, the time and the appropriate conditions to do so, based on Integrated Pest Management[148].

Subsequently, in rice crops and nearby natural areas, a characterization of the diversity of insects and spiders was performed for the first time. A greater abundance and richness of insects was evidenced in native vegetation patches (riparian forest) compared to rice cultivation, demonstrating the importance of proper management of these areas that act as reservoirs and/or refuges of species[149][150].

8.4. Forestry production

The last century showed a progressive increase in the forest area in the country, mainly eucalyptus; however, until the approval of the Second Forestry Law in 1987, the forest resource was historically scarce. This, in part, explains the little importance assigned to phytosanitary problems at that time[7].

In historical phytosanitary terms, the regulatory framework that constituted the Agricultural Defense Law of 1911 and its Regulatory Decree of 1912 to which we have already referred was directed to horticultural production and extensive crops. In this low-impact framework, it is possible to mention in addition to the ants *Pissodes castaneus* (De Geer) and *Rhyacionia buoliana* (Denis &. Schiffermüller) in some species of pines; and *Gonipterus gibberus* (Gyllenhal), *Phoracantha semipunctata* (Fabricius) and *Platypus sulcatus* (Chapuis) in Eucalyptus (the latter also in poplars)[7]. The appearance of *Sirex noctilio* (Fabricius) in 1980 changed this situation in pines[151], which led seven years later to the introduction of the nematode *Beddingia siricidicola* (Bedding) from New Zealand[152], as well as *Anaphes* *nitens* (Girault) in 1941 from South Africa to control *G. gibberus*[17].

The dynamism that the sector acquired from the Second Forestry Law was reflected in an increase in commercial tree plantations, which went from 95,000 hectares in 1987 to 1,079,160 hectares in 2018 (85% Eucalyptus, 15% Pinus), together with the 835,349 hectares of natural forests to complete the forest universe[153]. As Martínez[48] indicates, this growing forestry sector initially benefited from a relatively benign health situation, due in part to the relative distance of plantations from the center of origin of the tree species. But its expansion, and the passing of time, soon led to the introduction of exotic insect pests. Indeed, more than half of the pests that currently affect eucalyptus entered the country after 1995. Martínez[48], citing several authors, indicated that this situation was favored not only by local factors, but also because of a worldwide acceleration in the rate of insect invasion as a consequence of a greater world trade in seeds, plants and wood packaging material, a global homogenization of planted tree species and climate change. In this framework, the pests reported since then are *Ctenarytaina eucalypti* (Maskell) in 1998[154], *Glycaspis brimblecombei* (Moore) in 2004[155], *Ctenarytaina spatulata* (Taylor), *Blastopsylla occidentalis* (Taylor)[156], and *Thaumasto-coris peregrinus* (Woodpecker and Del-lappe)[157] in 2008.

Various management tactics have been used, such as tree improvement, silvicultural management, chemical, or biological control for the abovementioned pests. Although the first one is common for the treatment of diseases, with some successful examples. Likewise, silvicultural control methods have been used to prevent infestation by some pests. Currently, the only insects that are managed by synthetic pesticides in Uruguayan forestry plantations are the leaf cutter ants, that are controlled with toxic baits. Apart from this pest, the use of synthetic pesticides is very restricted, given that around 90% of forest plantations are under certification schemes. Furthermore, synthetic pesticides are economically expensive and rarely effective against many of these pests. Thus, biological control has been a common pest management strategy in Uruguayan forestry and, to date, almost all forest insect pests considered important have natural enemies that have been (or are being) introduced in the context of classical Biological Control programs[48].

9. Teaching plant health

University teaching of entomology and pest control accompanied the development of agriculture throughout the past century and the present. One year after the Faculty of Agronomy was founded in 1907, André Bouyat joined the teaching staff as Professor of Zoology[158]. He had French origin and was also in charge of fisheries studies[159]. Similarly, the teaching of Zoology appears in the 1911 Curriculum as General Zoology in the first year, and as Agricultural Zoology and Entomology in the third year[160]. In the following study plans, 1953, 1963, 1989 and 2020, there has been an incorporation of an Entomology course in the first years of the career (second or third according to the Plan), and in the fourth-year courses oriented to the different productions (as such or integrated into other disciplines, within Plant Protection or Plant Production).

In 2001, the postgraduate courses "Biodiversity, conservation and management of natural enemies as regulators of insect populations" and "Phytosanitary protection in viticulture", as part of the Master in Viticulture, Enology and Management, with a double degree between the Faculty of Agronomy and SupAgro Montpellier, France, were opened. That same year, courses started within the Permanent Education program, aimed at boosting University of the Republic graduates.

From 2005 to the present, numerous courses were taught within the framework of the Master in Agricultural Sciences of the Faculty of Agronomy, some of them including leader foreign scientists. As part of these studies, many Master's theses were formulated, and from 2012, doctorate's theses began to be tutored.

10. Milestones in plant health development

As detailed throughout this review, which covers almost a century and a half, both at international level and in Uruguay, numerous confluent and contradictory processes developed that marked the evolution of plant health in Uruguay (see milestones in Figure 2 in Supplementary material). Numerous actors participated in these processes, including suppliers of phytosanitary inputs, regulatory authorities, teaching, research and extension institutes, as well as users and consumers in general.

Since the end of the 19th century, industrial crops increased by 357% in a short period of 23 years (1890 -1913) in Uruguay (section 2). This increase in production and the continuous entry of plant material from abroad led to the unwanted entry of exotic pests and their subsequent incidence. From the beginning (first and second decades of the 20th century), Uruguay understood the problem, forming a strong institutional framework (Central Commission for Honor and Technical Directorate for Agricultural Defense, Faculty of Agronomy, Phytotechnical Institute and National Seedbed La Estanzuela) that spared efforts in applying all the tools available in favor of crop health, in a close relationship with the outside world (section 3).

Likewise, the incorporation of synthetic insecticides in the 1940s-1950s resulted in their improper use in Uruguay and throughout the world. However, as time passed, many of the first insecticides ended up being banned due to negative connotations to both humans and the environment. This resulted in the incorporation of more benign insecticides into Uruguayan production systems (section 4).

An arsenal of research and alliances of the stakeholders involved took place, aimed at the application of biological and ethological control methods, genetic improvement (sections 5-7), and pest management programs (Integrated Production, Organic Production, Wide Area, Agroecology) (sections 8.1-2) in different productive headings (sections 8.3-4). Thus, with different rhythms and scopes, the reality of plant health in Uruguay was shaping. Consumers' greater awareness of food bound to sustainable production will have a strong impact on its evolution. Despite of these, it has not been possible to substantially modify the universe of pest control in the country, where inadequate management of chemical insecticides predominates. Therefore, new milestones in this regard are expected in future times.

11. Final considerations

Agriculture is one of the human activities with marked effects on the planet. It is a means of obtaining food for a growing humanity, but, at the same time, of affecting natural resources. It can improve human nutrition and the quality of life of the population and accompany the biological rhythms of nature, or contribute to increasing inequalities, poor working conditions, health effects, reduction of biodiversity and environmental degradation. These options have always been raised in Uruguay, although the intensification of agriculture in recent decades has stressed the dilemma.

Although the history of plant health in Uruguay includes a permanent search for rational pest management, applying innovative approaches and “environmentally friendly” phytosanitary tools, its scope is limited due to the inappropriate use of insecticides. There is a long way ahead in order to “reconcile agriculture with ecology”, which means balancing economic, social and environmental sustainability in decisions related to agricultural production.

Incentives for this process are the growing demands from consumers for safe food produced sustainably, properties that act as attributes of differentiation and valorization. It is necessary to increase the stimuli and controls from the Government that favor the transition towards this agriculture, together with constant efforts on education regarding this problem, as well as research, innovation and dissemination on good agricultural practices. In such way, it will be possible to improve Uruguay's international insertion as a producer of high-quality food under parameters of social and environmental protection.

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Author contribution statement

CB wrote the article. XC-S contributed to the writing of some sections of the article, reviewed and edited its content, and prepared the table and figure.

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Supplementary material

Figure 2. Time-table of milestones in pest management in Uruguay