An Analysis of Successes in Biological Control of Insects in the Pacific Area*

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This analysis is designed to explore the validity of some hypotheses associated with biological control research and results, and to learn whether any "common denominators" for success seem to be evident among the now rather numerous cases of biological control. For instance, one of the most common ideas is that certain environments, particularly islands, are especially suitable for biological control. This study is based primarily on a consideration of 125 more or less successful cases of biological control of insect pests by *imported* natural enemies in 23 "countries" in the Pacific area. However, it is written against a background study of some 221 world-wide cases of biological control in about 65 countries. Conclusions drawn from the Pacific area cases (over half of the world total) are essentially the same as would be drawn from a consideration of cases throughout the world.

Evaluation of achievements in pest control from biological control projects is often difficult because of lack of adequate published documentation, hence individual cases certainly may be subject to reassessment, but it is felt that the large number of cases considered should make important trends readily apparent.

Success is a relative thing, but here we shall measure it in an economic sense; hence, outstanding successes refer to complete biological control being obtained and maintained against a major pest of a major crop over a fairly extensive area so that insecticidal treatment becomes rarely, if ever, necessary. Substantial successes will include cases where economic savings are somewhat less pronounced by reason of the pest or crop being less important, by the crop area being restricted (such as on a small island), or by the control being such that occasional insecticidal treatment is indicated.

Partial successes are those where chemical control measures remain commonly necessary but either the intervals between necessary applications are lengthened or results are improved when the same treatments are used or outbreaks occur less frequently. This category may also include cases where complete biological control is obtained only in a minor portion of the pest-infested area, or where entomophagous insects are only partially responsible for control results, as well

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as insufficiently substantiated cases. Some of these latter may include completely successful cases which merely have not been adequately documented in the literature. Partial successes tend to be overlooked or discounted but nonetheless they often represent a considerable savings as measured by reduction in damage or lessened need for treatment. Separation of the above-mentioned categories, one from the other, is, of course, arbitrary and open to interpretation, and additional information may necessitate changes.

It is emphasized that these successes resulted from importation projects. No cases of naturally occurring biological control are included; to attempt this would require a book. Neither are cases of biological control by micro-organisms or biological control of weeds included here. Also, the few cases of biological control by higher organisms, such as amphibians, birds, and mammals, are purposely omitted in order to restrict the analysis to the insect parasites and predators which have been responsible for the great majority of successes in biological control of insect pests.

The tabulation of data on biological control successes is given in separate tables for purposes of analysis, clarity of presentation, and ease of discussion. There is not space to include details on all known successful projects, but such details and literature references are available in the author's files, and have been used to develop the data herein presented. Table 1 lists Pacific area examples under the host (pest) species and includes the "country" of occurrence, type of natural enemy involved (parasite or predator) and the degree of success. In

TABLE 1. Cases of biological control of pest insects in the Pacific area by imported entomophagous insects.

Pest Species	Country of Occurrence	Type of Natural Enemy*	Control Results†
HOMOPTERA			
Aleurocanthus spiniferus (Quaintance)	Japan	par.	C
	Guam	par.	S
Aleurocanthus woglumi Ashby	Mexico	par.	C
	Costa Rica	par.	C
	Panama	par.	C
Aonidiella aurantii (Maskell)	USA (Cal.)	par.	P
	Australia	par.	P
Aonidiella citrina (Coquillett)	USA (Cal.)	par.	S
Aphis sacchari Zehntner	USA (HAW.)	comp.	S
Aspidiotus destructor Signoret	Fiji	pred.	C
	Bali	par.	P
Asterolecanium variolosum (Ratzeburg)	N. Zeal.	par.	S
	Tasmania	par.	P
Brevicoryne brassicae (L.)	Australia	par.	P
Ceroplastes rubens Maskell	Japan	par.	C
Chromaphis juglandicola (Kaltenbach)	USA (Cal.)	par.	P
Ericoccus coriaceus Maskell	N. Zeal.	pred.	C
Erisoma lanigerum (Hausmann)	N. Zeal	par.	C
	Australia	par.	S
	Canada (B.C.)	par.	C

* par. = parasite; pred. = predator; comp. = a complex.
† C = complete; S = substantial; P = partial.

	Chile	par.	C
	Colombia	par.	C
	Costa Rica	par.	C
	Japan	par.	C
	Peru	par.	S
	Tasmania	par.	S
	USA (Pac. Northwest)	par.	C
	USA (Cal.)	par.	S
Icerya aegyptiaca (Douglas)	Caroline I.	pred.	S
Icerya montserratensis Riley and Howard	Ecuador	pred.	S
Icerya palmeri Riley and Howard	Chile	pred	P
Icerya purchasi Maskell	USA (Cal.)	pred.	C
	USA (Haw.)	pred.	C
	Chile	pred.	C
	Guam	pred	C
	Japan	pred.	C
	New Zealand	pred.	C
	Peru	pred.	C
Lecanium (*Eulecanium*) *coryli* (L.)	Canada (B.C.)	par.	S
Lecanium (*Eulecanium*) *persicae* (Fabricius)	Australia	par.	S
Lepidosaphes beckii (Newman)	USA (Cal.)	par.	P
	Mexico	par.	S
Lepidosaphes ficus (Signoret)	USA (Cal.)	par.	P
Lepidosaphes ulmi (L.)	Canada (B.C.)	pred.	P
Macrosiphum pisi (Harris)	USA (Cal.)	par.	S
Myzocallis annulata (Hartig)	Tasmania	par.	P
Nipaecoccus nipae (Maskell)	USA (Haw.)	par.	S
Parlatoria oleae (Colvée)	USA (Cal.)	par.	S
Perkinsiella saccharacida Kirkaldy	USA (Haw.)	pred.	C
Phenacoccus iceryoides Green	Celebes	pred.	S
Phenacoccus aceris (Signoret)	Canada (B.C.)	par.	C
Pineus boerneri (Annand)	N. Zeal.	pred.	P
Pinnaspis buxi (Bouché)	USA (Haw.)	pred.	S
Pinnaspis minor (Maskell)	Peru	comp.	P
Planococcus citri (Risso)	USA (Cal.)	comp.	P
	Chile	comp.	P
	USA (Haw.)	par.	P
Pseudaulacaspis pentagona (Targioni-Tozzetti)	Peru	par.	S
Pseudococcus spp.	Australia pred.	pred.	S
Pseudococcus filamentosus Cockerell	USA (Haw.)	par.	P
Pseudococcus gahani Green	USA (Cal.)	par.	C
	Chile	par.	S
Pseudococcus adonidum (L.)	USA (Cal.)	par.	P
Quadraspidiotus (*Aspidiotus*) *perniciosus* (Comstock)	USA (Cal.)	par.	P
Saissetia oleae (Bernard)	USA (Cal.)	par.	S
	Australia	par.	P
	Peru	par.	S
	Chile	par.	P
Saissetia nigra (Nietner)	USA (Cal.)	par.	S
Siphanta acuta (Walker)	USA (Haw.)	par.	S
Tarophagus (*Megamelus*) *proserpina* (Kirkaldy)	USA (Haw.)	pred.	S
	Guam	pred.	S
	Caroline I.	pred.	P
Therioaphis maculata (Buckton)	USA (Cal.)	par.	S
Trialeurodes vaporariorum (Westwood)	Australia	par.	S
	Tasmania	par.	S
Trionymus sacchari (Cockerell)	USA (Haw.)	par.	S
Typhlocyba froggatti Baker (= *australis* Froggatt)	Tasmania	par.	P
LEPIDOPTERA			
Bedellia orchilella Walsingham	USA (Haw.)	par.	P
Chilo suppressalis (Walker)	USA (Haw.)	par.	P
Harrisina brillians Barnes and McDunnough	USA (Cal.)	par.	S

Laphygma exempta (Walker)	USA (Haw.)	par.	P
Laspeyresia nigricana (Stephens)	Canada (B.C.)	par.	S
Levuana iridescens Bethune-Baker	Fiji	par.	C
Lithocolletis messaniella Zeller	N. Zeal.	par.	P
Pieris rapae (L.)	N. Zeal.	par.	S
	Australia	par.	P
	Tasmania	par.	P
Plutella maculipennis (Curtis)	Australia	par.	P
	N. Zeal.	par.	S
	Tasmania	par.	P
Pseudaletia (Cirphis) unipuncta (Haworth)	USA (Haw.)	par.	P
Stilpnotia salicis (L.)	USA (Pac. Northwest)	par.	S
	Canada (B.C.)	par.	S
Tirathaba trichogramma Meyrick	Fiji	par.	P
COLEOPTERA			
Adoretus sinicus Burmeister	USA (Haw.)	par.	P
Anomala orientalis Waterhouse	USA (Haw.)	par.	S
Brontispa longissima selebensis Gestro (=*froggatti* Sharp)	Celebes	par.	S
Brontispa mariana Spaeth	Mariana Is.	par.	S
Cosmopolites sordidus (Germar)	Fiji	pred.	P
Crioceris asparagi (L.)	USA (Wash.)	par.	P
Epilachna philippinensis Dieke	Guam	par.	P
Galerucella xanthomelaena (Schrank)	USA (Cal.)	par.	P
Gonipterus scutellatus Gyllenhal	N. Zeal.	par.	S
Hypera postica (Gyllenhal)	USA (Cal.)	par.	S
Promecotheca papuana Csiki	N. Brit.	par.	S
Promecotheca reichei Baly	Fiji	par.	C
Rhabdoscelus obscurus (Boisduval)	USA (Haw.)	par.	S
Syagrius fulvitarsis Pascoe	USA (Haw.)	par.	P
DIPTERA			
Ceratitis capitata (Wiedemann)	USA (Haw.)	par.	P
Dacus cucurbitae Coquillett	USA (Haw.)	par.	P
Dacus dorsalis Hendel	USA (Haw.)	par.	S
Dasyneura mali Kieffer	N. Zeal.	par.	P
Dasyneura pyri (Bouché)	N. Zeal.	par.	S
Phytomyza ilicis (Curtis)	Canada (B.C.)	par.	P
Musca domestica L.	Fiji	pred.	P
ORTHOPTERA			
Gryllotalpa africana Palisot de Beauvois	USA (Haw.)	par.	P
Oxya chinensis (Thunberg)	USA (Haw.)	par.	S
Periplaneta americana (L.); *P. australasiae* (Fabricius)	USA (Haw.)	par.	P
Sexava nubila (Stål)	Celebes	par.	P
HYMENOPTERA			
Pristiphora erichsonii (Hartig)	Canada (B.C.	par.	S
DERMAPTERA			
Forficula auricularia L.	Canada (B.C.)	par.	P
	USA (Wash.)	par.	P
HEMIPTERA			
Nezara viridula (L.)	Australia	par.	S

addition to the cases listed in Table 1 there are several which have not been included there because of insufficient documentation or lack of data. Among these possible successes are: (1) the garden looper, several bruchid seed weevils, and the coconut and sugar-cane leaf rollers in Hawaii; (2) the rice armyworm, the rice leaf roller, and the banana moth in Fiji; (3) the citrophilus mealybug, and the Sirex pine sawfly in New Zealand· (4) a whitefly in Celebes; (5) the banana stem borer in Australia; (6) the coconut rhinoceros beetle in various Pacific islands; (7) the diamond back moth in Java and Sumatra; and (8) *Anomala sulcatula* Burm. in Saipan.

Table 2 shows the total cases of biological control according to country and degree of success. Table 3 summarizes the total number of cases of biological control according to whether they occurred on islands or continents.

TABLE 2. Cases of biological control of pest insects in the Pacific area by "countries."

	Control Results*			
	C	S	P	Total
Australia		5	5	10
Bali			1	1
Bismark Archipelago		1	1	2
Canada, British Columbia	2	4	3	9
Caroline Islands (incl. Ponape)		1	1	2
Celebes		2	1	3
Chile	2	1	3	6
Columbia	1			1
Costa Rica	2			2
Ecuador		1		1
Fiji	3		3	6
Japan	4			4
Mariana Islands (incl. Guam)	1	3	1	5
Mexico	1	1		2
New Zealand	3	5	3	11
Panama	1			1
Peru	1	3	1	5
Tasmania		2	5	7
U.S.A., California	2	9	8	19
U.S.A., Hawaii	2	10	12	24
U.S.A., Pacific Northwest	1	1	2	4
	26	49	50	125

* C = complete, S = substantial, P = partial.

TABLE 3. Cases of biological control of pest insects in the Pacific area: islands vs. continents.

	Control Results			
	Complete	Substantial	Partial	Total
Islands	13	24	28	65
Continents	13	25	22	60
			Total	125

It would naturally be hoped that an analysis of the more than 120 Pacific-area cases involving at least 87 species of pests which are controlled to a greater or less degree by natural enemies in some 23 "countries" or islands might reveal one or several common denominators characterizing successful natural enemies which could point the way for future work. Such an idea is not new, and previous workers have presented various hypotheses as to why particular natural enemies controlled, or failed to control, particular hosts in particular countries or islands. Some of these hypotheses stated in effect: (1) biological control works better on islands; (2) parasites are better than predators (or vice versa); (3) monophagous enemies are better than polyphagous enemies (or vice versa); (4) many species of enemies (attacking one host species) are better than one; (5) egg parasites acting alone are ineffective; (6) complete biological control following an introduction must occur rapidly (three years or three host generations) or else will not be complete; (7) sessile hosts—particularly Coccidae—are more amenable to biological control than other types; (8) the natural enemy should come from the same host in the country of origin; (9) natural enemies should be imported from areas ecologically equivalent ("ecological analogue" of Wilson, 1960) to the area of introduction; and (10) immigrant pests offer the best opportunities for biological control. Various of these hypotheses (perhaps especially nos. 3, 4, 8, 9, and 10) involve procedures or broad biological principles of undoubted importance and therefore definitely indicate initial direction for research on new projects.

Although the weight of evidence may seem to support some of the other hypotheses as stated, I believe that the observed results have sometimes been attributed to the wrong causes. There are important exceptions or qualifications to each of the preceding hypotheses so that to generalize in advance regarding chances of success would be to risk the possibility of dooming a new project by precluding important trials of one sort or another. For example, study of all known cases shows that complete biological control has occurred in nearly all types of plant environments with many types (groups) of pests and has been brought about by egg parasites, larval parasites, or pupal parasites acting substantially alone; by predators acting substantially alone, as well as by various combinations of parasites and/or predators acting together. Actually, more biological control successes have occurred world-wide on continents than on islands, although about 52 percent of the successes in the Pacific area were on islands (Table 3). Fairly monophagous species usually seem to do the best job, but there are important exceptions. Also, natural enemies obtained from other host species in the country of origin sometimes have been strikingly successful, as have natural enemies imported from areas not ecologically equivalent. Native pests also have been controlled by imported natural enemies. That a complete case of biological control will occur usually seems to be evident within two or three years, but occasional exceptions to this occur, such as with *Gonipterus* in certain areas of South Africa. The chances of success may seem to be greater if we proceed in a certain direction with a new project, but this should not influence the eventual exploration of alternative possibilities if the first leads fail. As Wilson (1960) says, "It is strange to reflect that although there are so many examples of successful biological control in the world, we cannot give an adequate account of why these particular examples were successful."

At the risk of being anticipatory by presenting conclusions before discussing all of the evidence, and for purposes of emphasis, the following broad summarization regarding the expectancy of success with new projects in biological control is presented.

Over a period of time, the number of successes attained will be proportional to the amount of research and importation work carried out. It should go without saying that this carries the implication of work directed along lines which appear to be the most suitable both biologically and ecologically. The emphasis, however, is on the necessity for work and more work. Of course, with transfer projects, such as those involving previously demonstrated success in another country and the transfer of the natural enemies responsible, chances of success are good with only a minimum of effort. The importance of the "amount of effort expended" idea lies in the realization that there are no mystical or specifically peculiar features that make Hawaii, Fiji, or California outstandingly favorable for biological control. Table 4 shows that more cases of biological control have occurred outside the tropics than in them. About 56 percent of the successes have occurred north or south of 30° latitude. Table 5 gives the leading countries in biological control and shows that areas having cool temperate climates such as British Columbia, New Zealand, and Tasmania have had more than their share of successes; however, they have also done much more than their share of investigation and importation of natural enemies. Hawaii, which leads in recorded successes, has been continuously and very vigorously active in biological control research and has led in importation work since the 1890's; California, the runner-up in successes, is probably also second in the number of importations carried out. It will also be noticed that British commonwealths, islands, or possessions are prominent among the successes. This is because earlier Commonwealth and British colonial entomologists stressed biological control work, as Tothill, Taylor, and Paine did in Fiji, and more recently the Commonwealth Institute of Biological Control and various Commonwealth governments have strongly supported and cooperated in such work. Were we to be more personal, many of the successes in biological control could be rather closely correlated with certain enthusiastic workers who have kept the work going and who have obtained support for their projects. About one-third of the countries doing work in biological control in the Pacific area have produced nearly three-fourths of the successful cases. Actually, many of the "countries" listed in Table 1 as having only one or two successes did little or no basic work themselves but obtained these by the transfer of natural enemies from countries which had already attained successes. Such transfer is not to be discouraged, but imagine how much more could be done if all countries actively supported foreign exploration and importation work.

TABLE 4. Cases of biological control of pest insects in the Pacific area according to latitude.

Latitude N. & S.	Control Results			
	Complete	Substantial	Partial	Total
0–10	3	7	4	14
10–20	6	4	5	15
20–30	3	11	12	26
30–40	10	17	18	45
40–50 or more	4	10	11	25
Total				125

TABLE 5. Leading countries in biological control of pest insects in the Pacific area.

Country	Control Results*				Approximate Latitude
	C	S	P	Total	
Hawaii, U.S.A.	2	10	12	24	20°–25° N
California, U.S.A.	2	7	8	17	30°–40° N
New Zealand	3	6	2	11	35°–45° S
Australia		5	5	10	30°–40° S
British Columbia, Canada	2	4	3	9	48°–55° N
Fiji	3		3	6	15°–20° S
Chile		2	5	7	40°–45° S
Tasmania, Australia	2	1	3	6	30°–40° S
Peru	1	3	1	5	10°–20° S
Japan	4			4	30°–40° N
Total cases	19	38	42	99	

* C = complete, S = substantial, P = partial.

The theory that islands, as such, are appreciably more conducive to success in biological control no longer is tenable. World-wide, about 31 islands and 34 countries on continents have reported successes. Some 55 percent of these successes have occurred on continents and of the complete successes nearly 60 percent have occurred on continents. In the Pacific area about 52 percent of the successes occurred on islands with the number of complete and substantial cases being essentially the same on islands and continents. Additionally, perhaps the level of success on islands has been overemphasized with respect to those occurring on continents for, as Wilson (1960) points out, "It is no disparagement of the remarkable successes obtained in some islands to point out that similar control over an equal area on a large continental mass would usually be regarded as partial success of little value." What Wilson means is that complete control is less likely to occur over a geographically extensive and ecologically varied area than in a fairly local and ecologically uniform environment, and he goes on to say, "It is unrealistic . . . to expect a single species of natural enemy to provide adequate control of its host over the whole area that the pest occupies in a continent." To the extent that islands have uniform habitats, have a large proportion of their crops and pests introduced, and practice intensive agriculture (which may emphasize pest problems as well as research on them) they are favorable areas for successful biological control. However, this applies just as well to continental areas having similar qualities.

It is clear that most of the importation work in biological control has been done by a few countries, territories, islands, or states and that successes have occurred more or less in proportion to the number of importations as exemplified by Hawaii, California, New Zealand, Australia, and British Columbia. The proportion of successes to introductions or of introductions to establishment has probably been as high or higher in British Columbia (41 species imported against 21 pests with six complete and three partial successes, McLeod 1951, 1954) and New Zealand (24 species colonized against 12 pests with 11 species established; Miller, Clark, and Dumbleton 1936) as in any of the subtropical or tropical areas. One obvious reason why certain countries or areas have appeared to neglect biological control work is that they have not had so many problems from accidentally introduced pests. Really striking results are, of course, contingent upon a serious problem to start with, and the most serious problems often result from new pest immigrants.

Some other general conclusions emerging from a consideration of the various listed successes, as depicted in Tables 6, 7, and 8 are: (1) about 53 percent of the species controlled in the Pacific area (46 out of 87) have been Homoptera, and about 35 percent (31 out of 87) have been coccids (soft scales, armored scales, and mealybugs). The majority of the remainder have been Lepidoptera (13 species), Coleoptera (14 species), or Homoptera other than coccids (15 species) (Tables 6 and 7); (2) usually control has been ascribed to one dominant natural enemy (Table 8); (3) parasites have produced control about four times as frequently as predators (Table 8).

Various other conclusions can doubtless be drawn by the reader. These are left to him except for a discussion of the disproportionate number of cases that have occurred with coccids. Several reasons are seen for this: (1) coccids are easily transported and are among the most common of accidentally introduced pests, thus presenting more problems to be solved; (2) they often have occurred on expensive crops and have defied easy chemical control, thus there has been considerable economic pressure and backing for biological control attempts; (3) the early success with the cottony-cushion scale led to continued emphasis on biological control of coccids, especially on citrus; and (4) coccids have certain biological attributes which may make them more susceptible than the average pest to control by natural enemies, such as (a) their usual perennial host plants confer a degree of chronological host-population stability which is advantageous to parasites or predators, (b) mass immigration or emigration is not typical of coccid populations (many tend to be sessile); this also gives a

TABLE 6. Number of world cases in different countries of biological control of pest insects by imported entomophagous insects.

Order	Pacific Area		All Other Areas	
	No. Cases	No. Pest Sp. Involved	No. Cases	No. Pest Sp. Involved
Homoptera	76*	44	68†	19
Lepidoptera	17	13	18	11
Coleoptera	14	14	9	6
Diptera	7	7	0	0
Orthoptera	5	4	0	0
Hymenoptera	1	1	3	3
Dermaptera	2	1	0	0
Hemiptera	1	1	0	0
Totals	123	86	98	39

Total (world) 221 cases: 125 pest species

* 16 cases represent transfer of natural enemies of the cottony-cushion scale or the woolly apple aphid.
† 38 cases represent transfer of natural enemies of the cottony-cushion scale or the woolly apple aphid.

TABLE 7. Cases of biological control of pest Homoptera in the Pacific area.

	Number of Cases	Number of Pest Species Controlled
Aphididae	17	7
Diaspinae	14	11
Pseudococcinae	12	9
Coccinae	11	7
Monophlebinae	10	4
Aleurodidae	7	3
Cicadellidae	6	4
Psyllidae	1	1
	78	46

TABLE 8. Cases of biological control of pest insects in the Pacific area according to type of natural enemy.

Number of Species Principally Credited With Producing Control	Number of Cases		
	Parasite	Predator	A Complex: (Pred. & Par.)
1	75	23	
2	16		2
3–4	4		
5 or more	1		4
Totals	96	23	6

tendency toward host-population stability, and (c) most coccids are exposed in all developmental stages to natural enemy attack. The fact that coccids occur commonly in mild climatic areas would not seem to be an important reason because this applies to many other pest groups as well. As far as the natural enemies themselves are concerned, there is no apparent reason why those attacking coccids should be *inherently* more effective than those attacking many other groups of insects.

Because coccids are involved in such a large proportion of cases of successful biological control, naturally their particular groups of natural enemies would be proportionally heavy on a listing of the parasites and predators involved. Thus the Encyrtidae and Aphelinidae of the parasitic Hymenoptera and the Coccinellidae of the predatory Coleoptera would be strongly predominant in the list. This, it is re-emphasized, should not be taken to mean that the Encyrtidae and Aphelinidae contain most of the effective parasites. As more emphasis is brought to bear on other groups of pests, increasing numbers of parasites in other families will be found to be just as effective.

Although biological control work is receiving more emphasis than formerly, it is still largely neglected in many countries. We should do well to reexamine the resolution made in this same city of Honolulu back in 1924 by the Food Conservation Conference. This was reiterated by Otanes (1940) at the 6th Pacific Science Congress in 1939. The resolution states,

"*Whereas*, the excellent economic results that have been gained by the transportation of parasites and other natural enemies of injurious insects from one country to another as in Hawaii, on the mainland of the United States, in Italy France, New Zealand, Uruguay, Chile, South Africa, the Islands of Mauritius, and other places have fully justified continued and broader work in this direction and therefore larger expenditures of funds by government and smaller organizations, and

"*Whereas*, the transportation and introduction of such beneficial insects, to be successful and free from danger, usually involves technical studies of an enormously complicated chain of interactions of organisms;

"*Resolved*, that this Conference urges all governments and organizations undertaking work of this character to provide for the most expert scientific supervision for such work, to include skilled biologists trained in the study of parasitic and predatory forms of life, and to assist so far as possible in the creation of a much larger number of such trained men by encouraging the study in the higher educational institutions of the very numerous problems of natural control."

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