A general stereoselective method for the synthesis of cyclopropanecarboxylates. A new version of the homologous Horner–Wadsworth–Emmons reaction†

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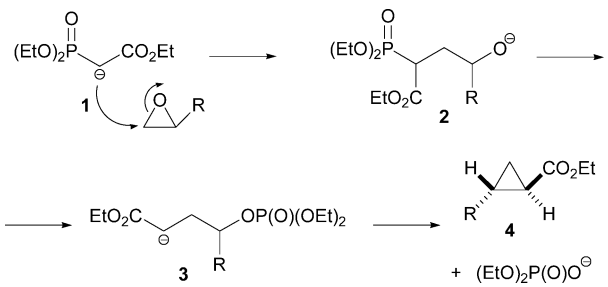
The synthesis of α-, β- and γ-substituted α-phosphono-γ-lactones was accomplished using different ring closure and ring homologation strategies. It was found that the lactones could be selectively transformed into the corresponding ethyl cyclopropanecarboxylates by treatment with sodium ethoxide in boiling THF. The reported reaction provides an attractive alternative to the classical homologous Horner–Wadsworth–Emmons approach to the construction of cyclopropanes with electron-withdrawing functionalities.

Introduction

The stereocontrolled synthesis of cyclopropanecarboxylates remains an important and active subject in organic chemistry due to the wide occurrence of these structural motifs in a number of biologically active natural products and several unnatural analogues.[1]

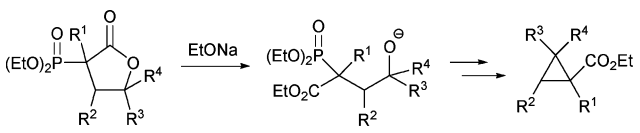
The homologous Horner–Wadsworth–Emmons (HWE)-type reaction of α-phosphonoalkanoate anions with epoxides provides an attractive route to differently substituted cyclopropanecarboxylates **4**.[2] The commonly accepted mechanism of this reaction, in particular that involving phosphonoacetate anion **1**, has been described as follows (Scheme 1).[2d,e]



Scheme 1

The cyclopropanation is initiated by epoxide ring opening (promoted by the anion **1**), leading to the γ-oxyalkylphosphonates **2**, which are then converted into the phosphates **3** by 1,4-migration of a phosphoryl functionality from carbon to oxygen. Subsequent γ-elimination of the elements of phosphoric acid from the latter results in a cyclopropane ring closure. Surprisingly, despite the evident synthetic advantage, this cyclopropanation reaction has not found wider application.[3]

The crucial role of γ-oxyalkylphosphonates in the formation of cyclopropanecarboxylates and their potentially easy accessibility by independent preparative methods prompted us to attempt modification of the standard homologous Horner–Wadsworth–Emmons reaction procedure. We believed that we would be able to generate γ-oxyalkylphosphonate anions **6** with different substitution patterns and to transform them into the corresponding cyclopropanecarboxylates **7** using a novel, simple and effective reaction sequence. We showed that an alternative and convenient source of the anions **6** could be the base-catalyzed ethanolysis of the appropriate α-phosphono-γ-butyrolactones **5**.[4] Futher conversion of these anions into the target cyclopropanecarboxylates **7** was realized using consecutive reaction steps and preparative procedures similar to those involved in the classical cyclopropanation. Additionally, we observed that this modified version of cyclopropanation was highly stereoselective. The substituted α-phosphono-γ-lactones of various regio- and stereochemistry were cleanly transformed into individual diastereoisomeric cyclopropanes (Scheme 2).



5,6,7	R^1	R^2	R^3	R^4
a	H	H	H	Me
b	CH_2=$CHCH_2$	H	H	H
c	PhCH=$CHCH_2$	H	H	H
d	Bn	H	H	H
e	H	n-Bu	Me	Me
f	H	$(CH_3)_2C$=CH	Me	Me
g	CH_2=$CHCH_2$	H	H	Me
h	Bn	H	H	Me

Scheme 2

In our previous work on a novel approach to cyclopropanecarboxylates, we generally used readily obtainable and simple α-phosphono-γ-lactones **5** as model substrates. We hoped that broad

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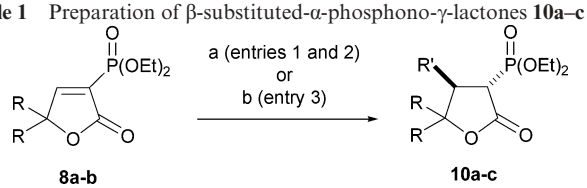
access to more functionalized starting materials would allow us to recognize better the scope of the synthesis.

This paper reports on effective, stereoselective, and in a large part original preparation of a series of mono-, di- and trisubstituted α-phosphono-γ-lactones bearing alkyl, alkenyl and aryl substituents. We present the most favorable conditions and stereochemistry of the homologous Horner–Wadsworth–Emmons-like cyclopropanation reaction performed with all these lactones. An important correction concerning the relative configuration assigned to the previously reported α,β-disubstituted cyclopropanecarboxylates **7g** and **7h** is also included. Finally, we describe here successful attempts for the preparation of α-phosphono-γ-oxyalkanoate anions containing selected γ-electron-withdrawing groups and their employment as excellent substrates for the synthesis of cyclopropanecarboxylates functionalized with these groups on the β-carbon atom.

Table 1 Preparation of β-substituted-α-phosphono-γ-lactones **10a–c**



8a-b **10a-c**

Entry	R	R′	Product	Yield (%)
1	H (**8a**)	n-Bu (**9a**)	**10a**	64
2	H (**8a**)	Ph (**9b**)	**10b**	58
3	Me (**8b**)	Ph (**9b**)	**10c**	82

Reagents and conditions: a) R′MgBr (3 equiv.), CuI (cat.), THF, −78 °C, 2.5 h; b) R′MgBr (3 equiv.), CuI (cat.), Et_2O, 0 °C, 2.5 h.

Results and discussion

Conjugate addition of organometallic reagents to various α,β-unsaturated-α-phosphono-γ-lactones represents a mild, effective and fully *trans*-diastereoselective approach to the corresponding β-substituted-α-phosphono-γ-lactones.[5] We have already used the conjugate addition method to obtain the lactones **5e** and **5f** with β-located alkyl and alkenyl groups, respectively.[4] Now we want to extend this list by adding the lactones **10a–c**.

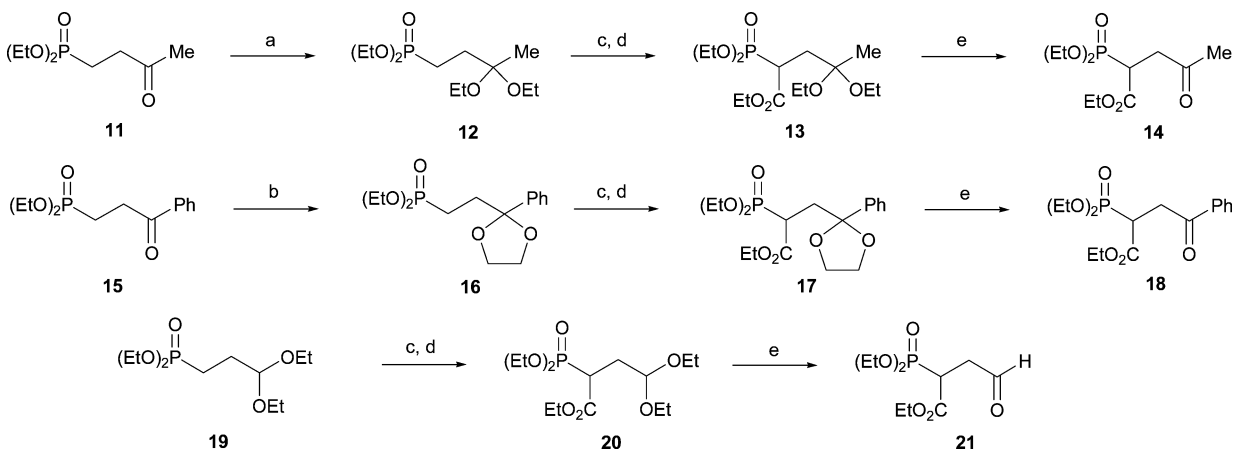
While the lactone **10c** was smoothly prepared by standard reaction of a simple α,β-unsatured lactone **8b**[5c,d] with phenylmagnesium bromide in the presence of CuI in diethyl ether at 0 °C, the preparation of the lactones **10a** and **10b** required a different protocol. Synthesis of the lactones **10a** and **10b** could be achieved in a satisfactory manner when the starting α,β-unsatured lactone **8a**[5a] was subjected to the reaction with a large excess (3 equiv.) of the corresponding Grignard reagents **9a** and **9b**, respectively, in the presence of CuI in THF at −78 °C (Table 1).

The *trans* stereochemistry of the lactone **10c** was assigned on the basis of ^1H and ^{13}C NMR data. The observed values of the coupling constants $^3J_{H3,H4}$ 12.2 Hz, $^3J_{P,H4}$ 15.7 Hz and $^3J_{P,C5}$ 13.6 Hz clearly proved the *trans* arrangement of the phosphoryl and phenyl groups.[5d] Unfortunately, the spectra of lactones **10a** and **10b** could not be interpreted unequivocally. Therefore, taking into account the method of preparation and the structural similarity of the lactones of **10c** and **10a,b**, we by analogy also assigned *trans*-stereochemistry to the lactones **10a** and **10b**.

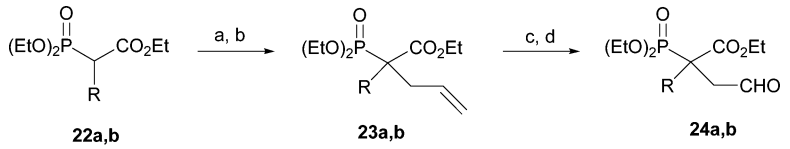
A separate strategy has been employed to carry out the synthesis of model α-alkyl, α-aryl-monosubstituted and α,γ-disubstituted-γ-lactones. We expected that particularly attractive precursors of these lactones would have the same carbon framework as α-phosphono-γ-hydroxyalkanoates, which could be obtained by a few consecutive, commonly known transformations of the appropriate γ-oxoalkylphosphonates or α-phosphono-γ-alkenoates.

Thus, the usual protection of carbonyl functionality in the selected γ-oxoalkylphosphonates **11**[6] and **15**[7] with triethyl orthoformate or ethylene glycol gave the ketals **12** and **16**. The ketals **12** and **16** as well as **19**[8] were then ethoxycarbonylated using Savigniac's well-known procedure.[9] Their metallation with LDA followed by ethoxycarbonylation of the resultant lithium derivatives with diethyl carbonate provided the appropriate α-phosphono-γ,γ-diethoxyalkanoates **13** and **20** and α-phosphono-γ-dioxolanylalkanoate **17**. Acid-catalyzed hydrolytic deprotection of the ethoxycarbonylated ketals **13**, **17** and **20** afforded α-phosphono-γ-oxoalkanoates **14**,[10] **18**[11] and **21**,[12] crucial intermediates in further projected transformations (Scheme 3).

Similarly, functionalized intermediates **24a** and **24b** with α-alkyl and α-aryl groups were synthesized in a two-step sequence



Scheme 3 *Reagents and conditions*: a) $(EtO)_3CH$, Amberlyst 15, 0 °C, 10 h; b) $HOCH_2CH_2OH$, *p*-TSA (cat.), toluene, reflux, 24 h; c) LDA, THF, −78 °C, d) $(EtO)_2C{=}O$, r.t., 20 h; e) 3 N HCl/THF, r.t., 24 h.



Scheme 4 *Reagents and conditions*: a) NaH, THF, 0 °C, 0,5 h; b) CH_2=$CHCH_2Br$, r.t., 20 h; c) EtOH, O_3, −78 °C; d) Me_2S, r.t., 20 h.

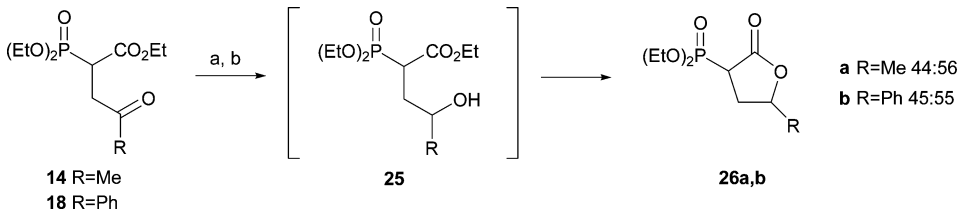
involving alkylation of generally accessible α-phosphonoalkanoates **22a** and **22b** with allyl bromide, and consecutive standard ozonolysis of the resulting allylation products **23a** and **23b** (Scheme 4).

With the α-phosphono-γ-oxoalkanoates **14**, **18**, **21** and **24a,b** in hand, we turned our attention to their effective conversion into various α-phosphono-γ-hydroxyalkanoates as well as a cyclization reaction of the latter producing designed, specific α-phosphono-γ-lactones. Thus, reduction of γ-oxoalkanoates **14** and **18** with KBH_4 smoothly afforded α-phosphono-γ-hydroxyalkanoates **25a,b**, while addition of n-BuMgBr and BnMgBr to the γ-oxoalkanoates **21**, **24a** and **24b** gave the γ-hydroxyalkanoates **27**. In both cases, the γ-hydroxyalkanoates formed underwent spontaneous cyclization under the reaction conditions, producing the target γ-alkyl- (**26a**, **26c**, **26d**), γ-aryl- (**26b**), α,γ-dialkyl- (**26e**, **26f**) and α-aryl-γ-alkyl- (**26g**, **26h**) substituted lactones as mixtures of inseparable diastereoisomers (Scheme 5 and Table 2).

Moreover, we developed a convenient homologation of some previously obtained α-unsubstituted α-phosphono-γ-lactones based on their alkylation reaction. Sequential treatment of α-phosphono-γ-lactones **26b**, **26c** and **26d** with LDA, and then with 3-methyl-2-butenyl bromide, allyl bromide or benzyl bromide, has proven useful as a concise entry to new α-alkyl-γ-aryl and α,γ-dialkyl-α-phosphono-γ-lactones **26i**, **26j**, **26k** and **26l**, respectively. All alkylation reactions proceeded with quite high stereoselectivity. Unfortunately, attempts to separate particular stereoisomers were unsuccessful (Table 3).

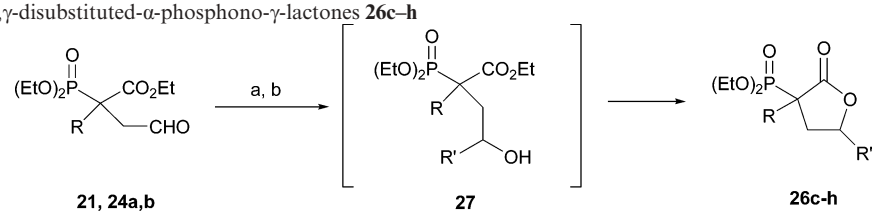
All the lactones prepared were subjected to the modified homologous HWE reaction under the previously optimized conditions. Treating these compounds with sodium ethoxide in THF–ethanol solution (100 : 2) at reflux for a few hours led to the expected cyclopropanecarboxylates in high or satisfactory yield (Tables 4 and 5).

^{1}H and ^{13}C NMR analysis revealed that the 2-substituted cyclopropanation products **27a**,[13] **27b**,[13] and **27c**[14] obtained from α-phosphono-γ-lactones **10a**, **10b** as well as **26b**, and **27c**, respectively, had the *trans*-configuration, while the products **27a**[13] and **27d**[15] derived from the lactones **26c** and **26d**, respectively, consisted of *trans* and *cis* stereoisomers, each in a ratio 93 : 7. Using NMR spectroscopy, we established also that 1,2-disubstituted cyclopropanecarboxylates **27e–l** were single diastereoisomers. However, the assignment of their configuration required a different approach. X-Ray crystallographic analysis carried out on 1-benzyl-2-phenylcyclopropanecarboxylic acid (which was prepared



Scheme 5 *Reagents and conditions*: a) KBH_4, MeOH, 0 °C, 1 h; b) 3 N HCl (aq.), r.t.

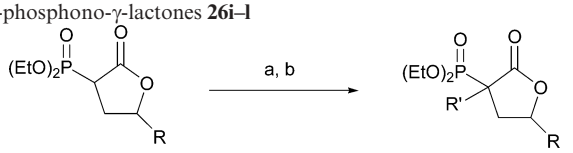
Table 2 Preparation of α,γ-disubstituted-α-phosphono-γ-lactones **26c–h**



Entry	R	R′	Yield (%)	Diastereoisomer ratio	Product
1	H (**21**)	n-Bu	70	56 : 44	**26c**
2	H (**21**)	Bn	75	67 : 33	**26d**
3	Me (**24a**)	n-Bu	68	80 : 20	**26e**
4	Me (**24a**)	Bn	71	80 : 20	**26f**
5	Ph (**24b**)	n-Bu	79	90 : 10	**26g**
6	Ph (**24b**)	Bn	75	92 : 8	**26h**

Reagents and conditions: a) R′MgBr, THF, 0 °C, 24 h; b) 1 N HCl (aq.).

Table 3 Preparation of α,γ-disubstituted-α-phosphono-γ-lactones **26i–l**

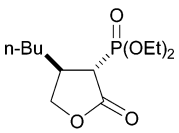
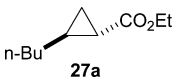
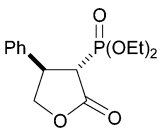
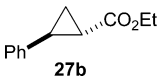
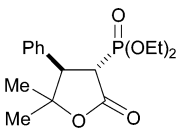
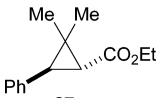
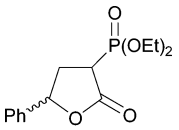
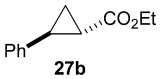
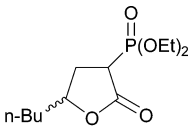
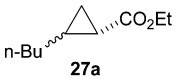
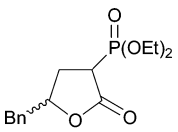
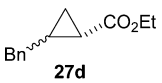


26b-d **26i-l**

Entry	R	R′	Yield (%)	Diastereoisomer ratio	Product
1	Ph (**26b**)	Bn	75	93 : 7	**26i**
2	Ph (**26b**)	$(CH_3)_2C{=}CHCH_2$	89	70 : 30	**26j**
3	n-Bu (**26c**)	Bn	78	84 : 16	**26k**
4	Bn (**26d**)	$CH_2{=}CHCH_2$	79	84 : 16	**26l**

Reagents and conditions: a) LDA, THF, −78 °C; b) R′MgBr, THF, −78 °C then r.t.

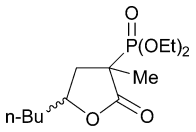
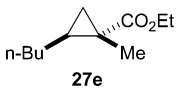
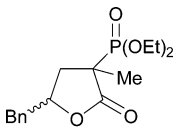
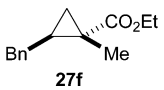
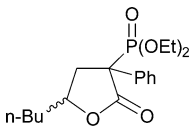
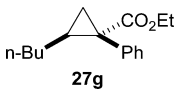
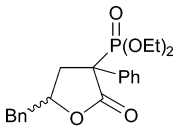
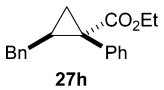
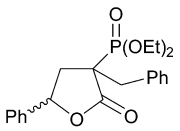
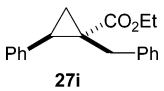
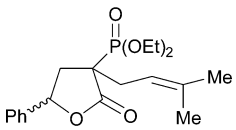
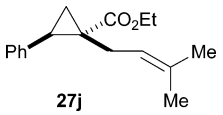
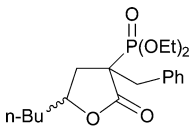
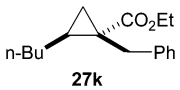
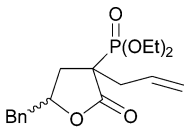
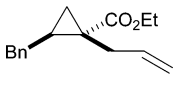
Table 4 Preparation of 2-substituted cyclopropanecarboxylates **27a–d**

Entry	Lactone	Reaction time/h	Product	Yield (%)
1	 **10a**	8	 **27a**	82
2	 **10b**	7	 **27b**	70
3	 **10c**	8	 **27c**	74
4	 **26b**	8	 **27b**	65
5	 **26c**	8	 **27a** *trans:cis* = 93:7	86
6	 **26d**	8	 **27d** *trans:cis* = 93:7	65

by base-catalyzed hydrolysis of the cyclopropanecarboxylate **27i**)[16] showed that the ring substituents of this compound remain in a *cis* relationship (Fig. 1). Details of the structure determination were published elsewhere.[17] Such a geometry unequivocally proves the *trans*-configuration of the parent cyclopropanecarboxylate **27i**.

This unexpected position of the "largest" groups in the representative 1,2-disubstituted cyclopropanation product disposed us to examine once again the structure of the previously described 1-benzyl-2-methylcyclopropanecarboxylate **7h**. The carboxylate **7h** was converted in a standard manner into the

Table 5 Preparation of 1,2-disubstituted cyclopropanecarboxylates **27e–l**

Entry	Lactone	Reaction time/h	Product	Yield (%)
1	 **26e**	8	 **27e**	55
2	 **26f**	8	 **27f**	53
3	 **26g**	8	 **27g**	58
4	 **26h**	8	 **27h**	62
5	 **26i**	8	 **27i**	80
6	 **26j**	6	 **27j**	74
7	 **26k**	8	 **27k**	62
8	 **26l**	8	 **27l**	61

dicyclohexylammonium salt of the parent acid,[18] which was analyzed by X-ray diffraction. Results of this analysis allowed us to assign *trans*-stereochemistry to the salt, and indirectly to the carboxylate **7h** (Fig. 2). The cyclopropane ring shows high level of the endocyclic C–C bond length asymmetry. The shortest bond is located opposite to the axial carboxylate group. This shortening of the distal bond presumably results from interactions of the endocyclic σ(C–C) and exocyclic antibonding π*(C=O) orbitals.[19] The crystal is constituted from centrosymmetric dimers in which all carboxylate groups are involved in the hydrogen bonding with the neighbouring dicyclohexylammonium cations.

The observed *trans* selectivity of the representative homologous HWE-type reactions providing 1,2-disubstituted cyclopropanecarboxylates entitles us to correct the previously reported *cis*-configuration of the carboxylates **7g** and **7h**.[4] On the other hand, it speaks simultaneously for *trans*-configuration for the

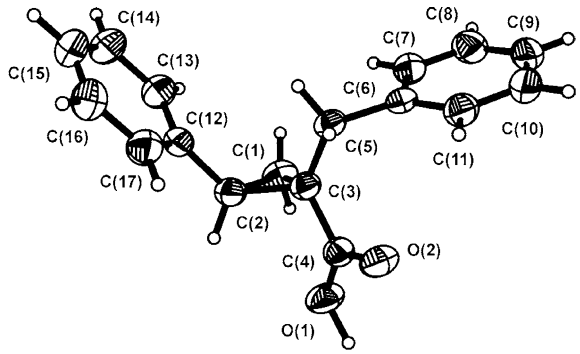


Fig. 1 The molecular structure of the cyclopropanecarboxylic acid derived from ester **27i** as published in ref. 17. Displacement ellipsoids are drawn at the 50% probability level. H atoms are represented by circles of an arbitrary radius. The endocyclic cyclopropane bond lengths are: C1–C2 1.480(2), C2–C3 1.540(2), C1–C3 1.510(2) Å.

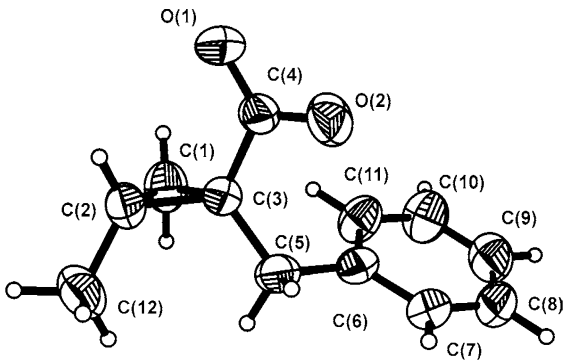
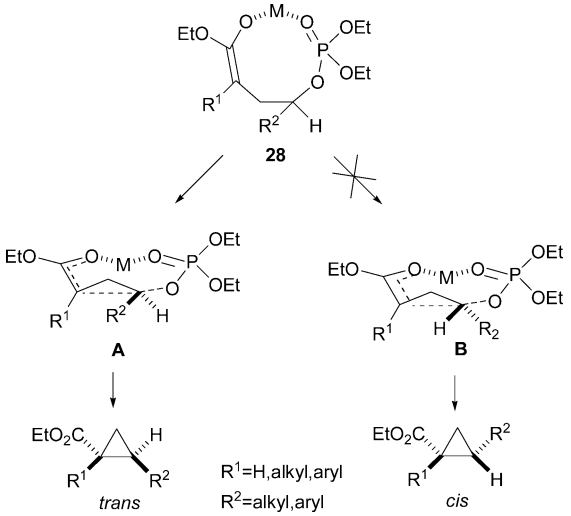


Fig. 2 The molecular structure of 1-benzyl-2-methylcyclopropanecarboxylate anion derived from the ester **7h**.† In the crystal the anion is hydrogen-bonded to the dicyclohexylammonium cation. The latter has been removed from the plot for clarity. Displacement ellipsoids are drawn at the 50% probability level. H atoms are represented by circles of an arbitrary radius. The endocyclic cyclopropane bond lengths are: C1–C2 1.475(2), C2–C3 1.523(2), C1–C3 1.514(2) Å.

remaining newly obtained cyclopropanecarboxylates **27e–h** and **27j–l**.

Such a stereochemical course of the cyclopropanation reaction can be rationalized by assuming that metal ion of the enolate intermediate involved in a ring closure is chelated by the oxygen atom of the P=O group. The resulting nine-membered complex **28** with an *E*- (rather than *Z*-) configured enolate functionality should be the predominant structure. The phosphate group in the chelate **28** undergoes intramolecular substitution by its enolate carbon atom according to steric requirements of a classical S_N2 mechanism. Of the two competitive pathways which are possible for this reaction, that with the transition state **A** minimizing the transannular steric interaction of the enolate substituent R^2 should be kinetically favored. Therefore, the chelates with $R^1 = H$ and R^2 = alkyl and/or aryl would be preferentially converted into *trans* 2-substituted cyclopropanecarboxylates. When both R^1 and R^2 were alkyl and/or aryl, the corresponding *trans*-1,2-disubstituted cyclopropanecarboxylates with *syn*-oriented substituents would be the dominant cyclization products (Scheme 6).

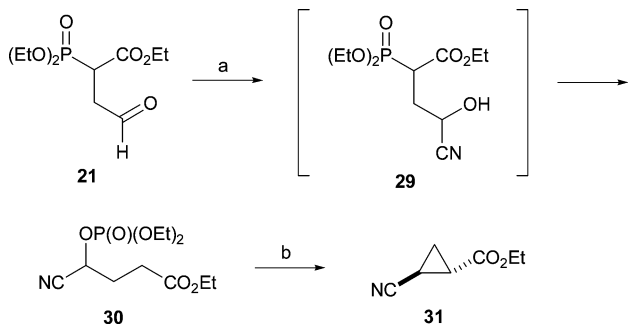
Intending to demonstrate the generality of our methodology, we attempted to employ it also for the preparation of cyclopropanecarboxylates with various functional groups on C-2. A



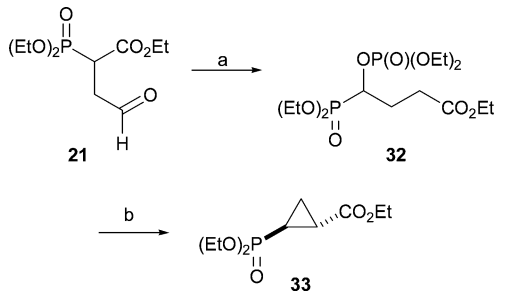
Scheme 6

particularly important objective of these attempts was the development of a simple approach to appropriately γ-functionalized-α-phosphono-γ-hydroxyalkanoate intermediates for the cyclopropanation reaction. We reasoned that such a type of compound should be accessible by nucleophilic addition of selected ambident anions or enolates to the already mentioned α-phosphono-γ-oxoalkanoates. We decided to use cyanide, diethyl phosphite and triethyl phosphonoacetate anions as model nucleophiles.

Surprisingly, the reaction of α-phosphono-γ-oxobutanoate **21** with acetone cyanohydrin serving as a cyanide anion equivalent[20] was found to proceed in a rather unexpected way (Scheme 7). The only isolated product of this reaction was neither α-phosphono-γ-cyano-γ-hydroxybutanoate **29** nor the corresponding α-phosphono-γ-cyanolactone but the γ-cyano-γ-phosphoryloxybutanoate **30** resulting from the previously mentioned 1,4-transfer of phosphoryl group from the α-carbon to the γ-oxygen atom within the first of these compounds. Similarly, hydrophosphonylation of the same γ-oxobutanoate **21** with diethyl phosphite in the presence of catalytic sodium ethoxide[21] afforded γ-phosphono-γ-phosphoryloxybutanoate **32** exclusively (Scheme 8). The butanoates **30** and **32**, when subjected to reaction with NaH in THF solution, readily underwent completely regioselective cyclization, providing *trans*-cyclopropanecarboxylates **31**[22] and **33**,[23] respectively.

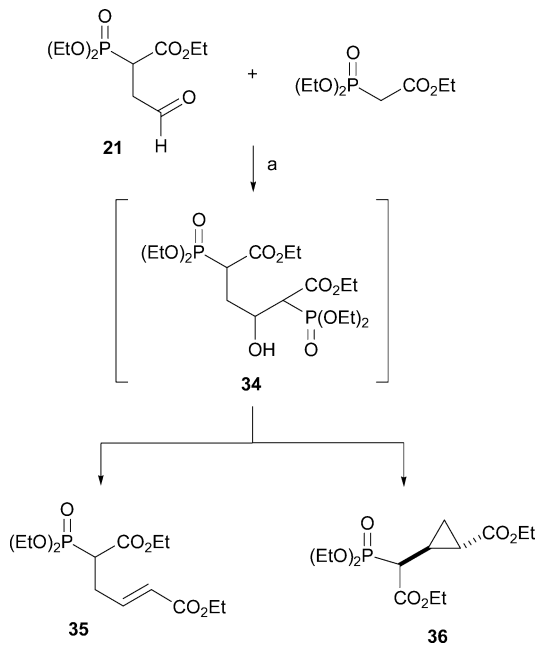


Scheme 7 *Reagents and conditions*: a) $(CH_3)_2C(OH)CN$, $Ti(OiPr)_4$, r.t., 20 h; b) NaH, THF, reflux, 5 h.



Scheme 8 *Reagents and conditions*: a) $(EtO)_2P(O)H$, EtOH, EtONa (cat.), rt, 0.5 h; b) NaH, THF, reflux, 5 h.

Considering the well-known chemical behavior of β- and γ-hydroxyalkylphosphonates bearing α-electron-withdrawing groups, one could have expected that the adduct **34** of triethyl phosphonoacetate anion and α-phosphono-γ-oxobutanoate **21** would be able to split off the elements of phosphoric acid by means of both the HWE reaction and its homologous version to give olefin **35** and cyclopropanecarboxylate **36**, respectively. To the best of our knowledge no reports have addressed direct competition between those two transformations. We established that the olefination and cyclopropanation reactions occurring with the adduct **34** were kinetically parallel and that they provided the expected products **35** and **36** in a 4 : 1 ratio. Both **35** and **36** were separated and their *trans*-stereochemistry was corroborated using NMR spectroscopy (Scheme 9).



Scheme 9 *Reagents and conditions*: a) NaH, THF, reflux, 5 h.

Conclusions

In summary, we have developed a concise and efficient synthesis of a variety of α-phosphono-γ-lactones. We have shown that such α-phosphono-γ-lactones can be efficiently transformed into the corresponding ethyl cyclopropanecarboxylates. It has been proven that 2-substituted and 1,2-disubstituted cyclopropanecarboxylates are formed as *trans* isomers exclusively. This method also allowed the synthesis of cyclopropanecarboxylates bearing C-2 electron-withdrawing substituents. The described approach to cyclopropanecarboxylates is equivalent to that of a conventional Horner–Wadsworth–Emmons-type cyclopropanation.

Experimental

General

NMR spectra were recorded on a Bruker DPX 250 instrument at 250.13 MHz for ^{1}H and 62.9 MHz for ^{13}C and 101.3 MHz for ^{31}P NMR, respectively, using tetramethylsilane as internal standard and 85% H_3PO_4 as external standard. The multiplicities of carbons were determined by DEPT experiments. IR spectra were measured on a Specord M80 (Zeiss) instrument. Elemental analyses were performed on a Perkin-Elmer PE 2400 analyzer. Melting points were determined in open capillaries and are uncorrected. Flash chromatography was carried out using Fluka silica gel 60 (230–400 mesh). Thin layer chromatography was carried out on commercially available pre-coated plates (Fluka Silica gel on TLC plates).

General procedure for the preparation of cyclopropanecarboxylates 27a–l. To a suspension of sodium hydride (0.14 g, 6.0 mmol) and α-diethoxyphosphoryl-γ-lactone **10a–c** or **26b–l** (6.0 mmol) in tetrahydrofuran (15 ml) was added dropwise under argon atmosphere at room temperature a solution of ethanol (0.40 ml, 6.6 mmol) in tetrahydrofuran (5 ml). The reaction mixture was stirred for 0.5 h and then was heated at reflux for the time given in Table 4 and Table 5. After cooling to room temperature, saturated NaCl solution (5 ml) was added and tetrahydrofuran was evaporated under reduced pressure. The residue was extracted with methylene chloride (3 × 15 ml) and dried (Na_2SO_4). After evaporation of the solvent under reduced pressure, the crude products were purified by column chromatography.

2-Butylcyclopropanecarboxylic acid ethyl ester (27a)[13]. Purification ($CHCl_3$, $R_f = 0.63$) gave the cyclopropanecarboxylate **27a** as a colourless oil (0.84 g, 82%); δ_H ($CDCl_3$) 0.68 (ddd, $^3J_{HH}$ = 9.7 Hz, $^3J_{HH}$ = 5.7 Hz, $^2J_{HH}$ = 4.0 Hz, 1H, C*H*H); 0.89 (t, $^3J_{HH}$ = 6.7 Hz, 3H, CH_3); 1.11–1.17 (m, 1H, CH*H*); 1.26 (t, $^3J_{HH}$ = 7.2 Hz, 3H, CH_3CH$_2$O); 1.30–1.38 (m, 8H, C*H*, C*H*, 3 × CH_2); 4.11 (q, $^3J_{HH}$ = 7.2 Hz, 2H, CH_2O).

2-Phenylcyclopropanecarboxylic acid ethyl ester (27b)[13]. Purification ($CHCl_3$–hexane 80 : 20, R_f = 0.50) gave the cyclopropanecarboxylate **27b** as a colourless oil (0.80 g, 70%); δ_H ($CDCl_3$) 1.26 (t, $^3J_{HH}$ = 7.0 Hz, 3H, CH_3CH$_2$O); 1.28–1.32 (m, 1H, C*H*); 1.58 (ddd, $^3J_{HH}$ = 8.5 Hz, $^3J_{HH}$ = 6.5 Hz, $^2J_{HH}$ = 4.2 Hz, 1H, C*H*H); 1.88 (ddd, $^3J_{HH}$ = 8.5 Hz, $^3J_{HH}$ = 5.2 Hz, $^2J_{HH}$ = 4.2 Hz, 1H, *C*H*H*); 2.52 (ddd, $^3J_{HH}$ = 9.0 Hz, $^3J_{HH}$ = 6.5 Hz, $^3J_{HH}$ = 5.2 Hz, 1H, C*H*); 4.17 (q, $^3J_{HH}$ = 7.0 Hz, 2H, CH_2O); 7.08–7.28 (m, 5H, CH_{Ar}).

2,2-Dimethyl-3-phenylcyclopropanecarboxylic acid ethyl ester (27c)[14]. Purification ($CHCl_3$–hexane 50 : 50, R_f = 0.36) gave the cyclopropanecarboxylate **27c** as a colourless oil (1.00 g, 85%); δ_H ($CDCl_3$) 1.05 (s, 3H, CH_3); 1.23 (t, $^3J_{HH}$ = 7.0 Hz, 3H, CH_3CH$_2$O);

1.56 (s, 3H, CH_3); 1.85 (d, $^3J_{HH}$ = 6.5 Hz, 1H, CH); 2.47 (d, $^3J_{HH}$ = 6.5 Hz, 1H, CH); 4.00 (q, $^3J_{HH}$ = 7.0 Hz, 2H, CH_2O); 7.20–7.39 (m, 5H, CH_{Ar}).

2-Benzylcyclopropanecarboxylic acid ethyl ester (27d)[15]. Purification ($CHCl_3$–hexane 50 : 50, R_f = 0.45) gave the cyclopropanecarboxylate **27d** as a colourless oil (0.53 g, 65%); δ_H ($CDCl_3$) 0.86 (ddd, $^3J_{HH}$ = 9.0 Hz, $^3J_{HH}$ = 6.0 Hz, $^2J_{HH}$ = 4.0 Hz, 1H, CHH); 1.24 (t, $^3J_{HH}$ = 7.0 Hz, 3H, CH_3CH$_2$O); 1.32 (ddd, $^3J_{HH}$ = 9.5 Hz, $^3J_{HH}$ = 6.2 Hz, 1H, $^2J_{HH}$ = 4.0 Hz, CHH); 1.50 (ddd, $^3J_{HH}$ = 9.0 Hz, $^3J_{HH}$ = 6.5 Hz, $^3J_{HH}$ = 6.2 Hz, 1H, CH); 1.67–1.78 (m, 1H, CH); 2.54 (dd, $^2J_{HH}$ = 14.0 Hz, $^3J_{HH}$ = 7.0 Hz, 1H, CHH); 2.76 (dd, $^2J_{HH}$ = 14.0 Hz, $^3J_{HH}$ = 6.5 Hz, 1H, CHH); 4.13 (q, $^3J_{HH}$ = 7.0 Hz, 2H, CH_2O); 7.20–7.31 (m, 5H, CH_{Ar}).

2-Butyl-1-methylcyclopropanecarboxylic acid ethyl ester (27e). Purification ($CHCl_3$–hexane 50 : 50, R_f = 0.27) gave the cyclopropanecarboxylate **27e** as a colourless oil (0.40 g, 55%); ν_{max} 1764; δ_H ($CDCl_3$) 0.59–0.70 (m, 1H, CHH); 0.82 (t, $^3J_{HH}$ = 6.7 Hz, 3H, CH_3); 1.07 (dd, $^3J_{HH}$ = 6.2 Hz, $^2J_{HH}$ = 3.7 Hz, 1H, CHH); 1.18 (t, $^3J_{HH}$ = 7.0 Hz, 3H, CH_3CH$_2$O); 1.20–1.37 (m, 6H, 3 × CH_2); 1.45 (s, 3H, CH_3); 1.78 (ddt, $^3J_{HH}$ = 9.2 Hz, $^3J_{HH}$ = 6.7 Hz, $^3J_{HH}$ = 6.2 Hz, 1H, CH); 4.08 (q, $^3J_{HH}$ = 7.0 Hz, 2H, CH_2O); δ_C ($CDCl_3$) 13.77 (CH_3); 14.18 (CH_3CH$_2$O); 18.68 (CH_3); 21.27 (CH_2); 23.13 (CH_2); 24.12 (CH_2); 29.27 (CH); 31.18 (CH_2); 33.74 (CH); 60.63 (CH_2O); 174.66 (C=O). $C_{11}H_{20}O_2$: requires C 71.70, H 10.94; found C 71.56, H 10.99.

2-Benzyl-1-methylcyclopropanecarboxylic acid ethyl ester (27f). Purification ($CHCl_3$–hexane 50 : 50, R_f = 0.41) gave the cyclopropanecarboxylate **27f** as a colourless oil (0.39 g, 53%); ν_{max} 1748; δ_H ($CDCl_3$) 1.18 (t, $^3J_{HH}$ = 7.0 Hz, 3H, CH_3CH$_2$O); 1.27 (dd, $^3J_{HH}$ = 6.5 Hz, $^2J_{HH}$ = 3.7 Hz, 1H, CHH); 1.46 (s, 3H, CH_3); 1.69 (dd, $^3J_{HH}$ = 9.0 Hz, $^2J_{HH}$ = 3.7 Hz, CHH); 2.00 (dd, $^2J_{HH}$ = 8.7 Hz, $^3J_{HH}$ = 5.0 Hz, 1H, CHH); 2.18–2.31 (m, 1H, CH); 3.12 (dd, $^2J_{HH}$ = $^3J_{HH}$ = 8.7 Hz, 1H, CHH); 4.18 (q, $^3J_{HH}$ = 7.0 Hz, 2H, CH_2O); 7.10–7.24 (m, 5H, CH_{Ar}); δ_C ($CDCl_3$) 13.06 (CH_3CH$_2$O); 17.73 (CH_3); 18.88 (CH_2); 29.11 (CH); 31.42 (CH_2); 33.40 (CH); 60.33 (CH_2O); 126.00 (2 × CH_{Ar}); 127.88 (CH_{Ar}); 127.65 (2 × CH_{Ar}); 138.48 (C$_{Ar}$); 171.47 (C=O). $C_{14}H_{18}O_2$: requires C 77.03, H 8.31; found C 77.27, H 8.27.

2-Butyl-1-phenylcyclopropanecarboxylic acid ethyl ester (27g). Purification ($CHCl_3$–hexane 50 : 50, R_f = 0.32) gave the cyclopropanecarboxylate **27g** as a colourless oil (0.53 g, 58%); ν_{max} 1768; δ_H ($CDCl_3$) 0.48–0.55 (m, 1H, CHH); 0.81 (t, $^3J_{HH}$ = 7.0 Hz, 3H, CH_3); 1.08 (dd, $^3J_{HH}$ = 6.5 Hz, $^2J_{HH}$ = 4.0 Hz, 1H, CHH); 1.15 (t, $^3J_{HH}$ = 7.2 Hz, 3H, CH_3CH$_2$O); 1.18–1.25 (m, 2H, CH_2); 1.27–1.38 (m, 4H, 2 × CH_2); 1.80 (ddt, $^3J_{HH}$ = 9.0 Hz, $^3J_{HH}$ = 6.5 Hz, $^3J_{HH}$ = 6.2 Hz, 1H, CH); 4.05 (q, $^3J_{HH}$ = 7.2 Hz, 1H, CHHO); 4.12 (q, $^3J_{HH}$ = 7.2 Hz, 1H, CHHO); 7.22–7.31 (m, 5H, CH_{Ar}); δ_C ($CDCl_3$) 13.99 (CH_3); 14.15 (CH_3CH$_2$O); 21.27 (CH_2); 22.39 (CH_2); 28.49 (CH_2); 29.96 (CH); 31.32 (CH_2); 33.74 (CH); 60.83 (CH_2O); 126.84 (CH_{Ar}); 127.79 (2 × CH_{Ar}); 131.32 (2 × CH_{Ar}); 136.52 (C$_{Ar}$); 174.66 (C=O). $C_{16}H_{22}O_2$: requires C 78.01, H 9.00; found C 78.12, H 8.97.

2-Benzyl-1-phenylcyclopropanecarboxylic acid ethyl ester (27h). Purification ($CHCl_3$–hexane 50 : 50, R_f = 0.41) gave the cyclopropanecarboxylate **27h** as a colourless oil (0.50 g, 62%); ν_{max} 1740; δ_H ($CDCl_3$) 1.20 (t, $^3J_{HH}$ = 7.0 Hz, 3H, CH_3CH$_2$O); 1.31 (dd, $^3J_{HH}$ = 7.0 Hz, $^2J_{HH}$ = 3.7 Hz, 1H, CHH); 1.79 (dd, $^3J_{HH}$ = 9.0 Hz, $^2J_{HH}$ = 3.7 Hz, 1H, CHH); 2.05 (dd, $^2J_{HH}$ = 8.5 Hz, $^3J_{HH}$ = 5.0 Hz, 1H, CHH); 2.18 (dddd, $^3J_{HH}$ = 9.0 Hz, $^3J_{HH}$ = 8.5 Hz, $^3J_{HH}$ = 7.0 Hz, $^3J_{HH}$ = 5.0 Hz, 1H, CH); 3.12 (dd, $^2J_{HH}$ = $^3J_{HH}$ = 8.5 Hz, 1H, CHH); 4.14 (q, $^3J_{HH}$ = 7.0 Hz, 2H, CH_2O); 6.94–7.33 (m, 10H, CH_{Ar}); δ_C ($CDCl_3$) 13.06 (CH_3CH$_2$O); 18.88 (CH_2); 29.11 (CH); 31.04 (CH_2); 33.40 (CH); 59.19 (CH_2O); 125.25 (2 × CH_{Ar}); 125.96 (2 × CH_{Ar}); 126.00 (CH_{Ar}); 126.78 (CH_{Ar}); 129.64 (2 × CH_{Ar}); 132.60 (2 × CH_{Ar}); 138.05 (C$_{Ar}$); 141.04 (C$_{Ar}$); 171.20 (C=O). $C_{19}H_{20}O_2$: requires C 81.40, H 7.19; found C 81.34, H 7.16.

1-Benzyl-2-phenylcyclopropanecarboxylic acid ethyl ester (27i). Purification ($CHCl_3$–hexane 50 : 50, R_f = 0.26) gave the cyclopropanecarboxylate **27i** as a colourless oil (1.22 g, 74%); ν_{max} 1764; δ_H ($CDCl_3$) 1.18 (t, $^3J_{HH}$ = 7.0 Hz, 3H, CH_3CH$_2$O); 1.41 (dd, $^3J_{HH}$ = 7.0 Hz, $^2J_{HH}$ = 5.0 Hz, 1H, CHH); 1.88 (dd, $^3J_{HH}$ = 9.2 Hz, $^2J_{HH}$ = 5.0 Hz, 1H, CHH'); 2.00 (d, $^2J_{HH}$ = 15.5 Hz, 1H, CHH); 2.84 (dd, $^3J_{HH}$ = 9.2 Hz, $^3J_{HH}$ = 7.0 Hz, 1H, CH); 3.20 (d, $^2J_{HH}$ = 15.5 Hz, 1H, CHH); 4.12 (q, $^3J_{HH}$ = 7.0 Hz, 1H, CHHO); 4.13 (q, $^3J_{HH}$ = 7.0 Hz, 1H, CHHO); 7.12–7.30 (m, 10H, CH_{Ar}); δ_C ($CDCl_3$) 14.01 (CH_3CH$_2$O); 17.78 (CH_2); 30.77 (CH_2); 31.00 (C); 32.52 (CH); 60.72 (CH_2O); 125.74 (2 × CH_{Ar}); 126.86 (2 × CH_{Ar}); 127.93 (CH_{Ar}); 128.24 (CH_{Ar}); 128.55 (2 × CH_{Ar}); 129.20 (2 × CH_{Ar}); 136.58 (C$_{Ar}$); 140.26 (C$_{Ar}$); 174.40 (C=O). $C_{19}H_{20}O_2$: requires C 81.40, H 7.19; found C 81.57, H 7.17.

1-(3-Methylbut-2-enyl)-2-phenylcyclopropanecarboxylic acid ethyl ester (27j). Purification ($CHCl_3$–hexane 80:20, R_f = 0.66) gave the cyclopropanecarboxylate **27j** as a colourless oil (0.96 g, 62%); ν_{max} 1764, 1664; δ_H ($CDCl_3$) 1.22 (dd, $^3J_{HH}$ = 7.2 Hz, $^2J_{HH}$ = 5.0 Hz, 1H, CHH); 1.27 (t, $^3J_{HH}$ = 7.0 Hz, 3H, CH_3CH$_2$O); 1.39 (s, 3H, CH_3); 1.57 (dd, $^2J_{HH}$ = 15.2 Hz, $^3J_{HH}$ = 6.7 Hz, 1H, CHH); 1.61 (s, 3H, CH_3); 1.66 (dd, $^3J_{HH}$ = 9.0 Hz, $^2J_{HH}$ = 5.0 Hz, 1H, CHH); 2.26 (dd, $^2J_{HH}$ = 15.2 Hz, $^3J_{HH}$ = 6.7 Hz, 1H, CHH); 2.81 (dd, $^3J_{HH}$ = 9.0 Hz, $^3J_{HH}$ = 7.2 Hz, 1H, CH); 4.17 (q, $^3J_{HH}$ = 7.0 Hz, 1H, CHHO); 4.18 (q, $^3J_{HH}$ = 7.0 Hz, 1H, CHHO); 5.59 (t, $^3J_{HH}$ = 6.7 Hz, 1H, CH); 7.19–7.32 (m, 5H, CH_{Ar}); δ_C ($CDCl_3$) 13.22 (CH_3CH$_2$O); 16.64 (CH_3); 24.72 (CH_2); 26.04 (CH_3); 29.45 (CH); 31.01 (C); 35,41 (CH_2), 59.65 (CH_2O); 120.90 (CH); 125.66 (2 × CH_{Ar}); 127.11 (CH_{Ar}); 128.29 (2 × CH_{Ar}); 131.15 (C); 135.90 (C$_{Ar}$); 173.88 (C=O). $C_{17}H_{22}O_2$: requires C 79.03, H 8.58; found C 78.87, H 8.54.

1-Benzyl-2-butylcyclopropanecarboxylic acid ethyl ester (27k). Purification ($CHCl_3$–hexane 50 : 50, R_f = 0.33) gave the cyclopropanecarboxylate **27k** as a colourless oil (1.25 g, 80%); ν_{max} 1740; δ_H ($CDCl_3$) 0.58 (dd, $^3J_{HH}$ = 6.0 Hz, $^2J_{HH}$ = 3.7 Hz, 1H, CHH); 0.91 (t, $^3J_{HH}$ = 6.7 Hz, 3H, CH_3); 1.12 (t, $^3J_{HH}$ = 7.0 Hz, 3H, CH_3CH$_2$O); 1.22–1.59 (m, 8H, 3 × CH_2, CHH, CH); 2.66 (d, $^2J_{HH}$ = 15.5 Hz, 1H, CHH); 3.23 (d, $^2J_{HH}$ = 15.5 Hz, 1H, CHH); 4.03 (q, $^3J_{HH}$ = 7.0 Hz, 1H, CHHO); 4.04 (q, $^3J_{HH}$ = 7.0 Hz, 1H, CHHO); 7.15–7.23 (m, 5H, CH_{Ar}); δ_C ($CDCl_3$) 13.87 (CH_3), 14.01 (CH_3CH$_2$O); 21.08 (CH_2); 22.45 (CH_2); 27.93 (CH_2); 28.03 (CH_2); 29.04 (C); 31.68 (CH); 33.46 (CH$_2$); 60.40 (CH$_2$O); 124.52 (CH_{Ar}); 128.02 (2 × CH_{Ar}); 128.53 (2 × CH_{Ar}); 140.72 (C$_{Ar}$); 175.31 (C=O). $C_{17}H_{24}O_2$: requires C 78.42, H 9.29; found C 78.67, H 9.27.

1-Allyl-2-benzylcyclopropanecarboxylic acid ethyl ester (27l). Purification ($CHCl_3$–hexane 50 : 50, R_f = 0.50) gave the cyclopropanecarboxylate **27l** as a colourless oil (0.24 g, 61%); ν_{max} 1720, 1640; δ_H ($CDCl_3$) 0.84 (dd, $^3J_{HH}$ = 6.5 Hz, $^2J_{HH}$ = 4.0 Hz,

1H, C*H*H); 1.20 (t, $^3J_{HH}$ = 7.0 Hz, 3H, C*H*$_3$CH$_2$O); 1.30 (dd, $^3J_{HH}$ = 9.0 Hz, $^2J_{HH}$ = 4.0 Hz, 1H, CH*H*); 1.52–1.60 (m, 1H, C*H*); 2.00 (dd, $^2J_{HH}$ = 15.7 Hz, $^3J_{HH}$ = 7.0 Hz, 1H, CH*H*); 2.12 (dd, $^2J_{HH}$ = 15.7 Hz, $^3J_{HH}$ = 6.0 Hz, 1H, C*H*H); 2.51 (dd, $^2J_{HH}$ = 12.0 Hz, $^3J_{HH}$ = 7.0 Hz, 1H, CH*H*); 2.74 (dd, $^2J_{HH}$ = 12.0 Hz, $^3J_{HH}$ = 6.0 Hz, 1H, C*H*H); 4.11 (q, $^3J_{HH}$ = 7.0 Hz, 2H, C*H*$_2$O); 5.07 (d, $^3J_{HH}$ = 9.7 Hz, 1H, CH*H*); 5.08 (d, $^3J_{HH}$ = 17.7 Hz, 1H, C*H*H); 5.90 (dddd, $^3J_{HH}$ = 17.7 Hz, $^3J_{HH}$ = 9.5 Hz, $^3J_{HH}$ = 7.0 Hz, $^3J_{HH}$ = 6.0 Hz, 1H, C*H*); δ_C (CDCl$_3$) 13.73 (*C*H$_3$CH$_2$O); 21.81 (*C*H$_2$); 22.12 (*C*H); 30.24 (*C*H$_2$); 32.11 (*C*); 61.11 (*C*H$_2$O); 114.75 (*C*H$_2$); 125.13 (2 × *C*H$_{Ar}$); 127.06 (*C*H$_{Ar}$); 128.69 (2 × *C*H$_{Ar}$); 135.21 (*C*H); 135.94 (*C*$_{Ar}$); 175.30 (*C*=O). $C_{16}H_{20}O_2$: requires C 78.65, H 8.25; found C 78.89, H 8.28.

4-Cyano-4-(diethoxyphosphoryloxy)butyric acid ethyl ester (30). To a solution of phosphonate **21** (0.80 g, 3.0 mmol) and acetone cyanohydrin (1.10 ml, 1.2 mmol) in methylene chloride (10 ml) titanium(IV) isopropoxide (0.89 g, 3.0 mmol) was added. The resulting solution was stirred at room temperature for 20 h. Water (10 ml) was added, the organic layer was separated and the aqueous layer was extracted with methylene chloride (2 × 15 ml). The combined organic layers were washed with 1 N HCl (5 ml) then dried (MgSO$_4$) and evaporated under reduced pressure. The residue was chromatographed (CHCl$_3$–acetone 90 : 10, R_f = 0.26) to give the ester **30** as a colourless oil (0.84 g, 95%); ν_{max} 2200, 1748, 1260, 1042; δ_P (CDCl$_3$) −2.14; δ_H (CDCl$_3$) 1.26 (t, $^3J_{HH}$ = 7.0 Hz, 3H, C*H*$_3$CH$_2$O); 1.35 (td, $^3J_{HH}$ = 7.0 Hz, $^4J_{PH}$ = 0.5 Hz, 3H, C*H*$_3$CH$_2$OP); 1.37 (td, $^3J_{HH}$ = 7.0 Hz, $^4J_{PH}$ = 0.5 Hz, 3H, C*H*$_3$CH$_2$OP); 2.30 (t, $^3J_{HH}$ = 6.5 Hz, 2H, C*H*$_2$); 2.52–2.63 (m, 2H, C*H*$_2$); 4.18 (q, $^3J_{HH}$ = 7.0 Hz, C*H*$_2$O); 4.20 (dq, $^3J_{PH}$ = $^3J_{HH}$ = 7.0 Hz, 4H, 2 × C*H*$_2$OP); 5.15 (dt, $^3J_{PH}$ = 8.5 Hz, $^3J_{HH}$ = 6.50 Hz, 1H, C*H*); δ_C (CDCl$_3$) ^{13}C NMR δ_C (CDCl$_3$) 13.24 (s, *C*H$_3$CH$_2$O); 15.74 (d, $^3J_{PC}$ = 5.8 Hz, *C*H$_3$CH$_2$OP); 15.80 (d, $^3J_{PC}$ = 5.6 Hz, *C*H$_3$CH$_2$OP); 25.04 (d, $^4J_{PC}$ = 3.7 Hz, *C*H$_2$); 28.87 (s, *C*H$_2$); 60.04 (s, *C*H$_2$O); 60.29 (s, 2 × *C*H$_2$OP); 69.11 (d, $^2J_{PC}$ = 6.7 Hz, *C*HO); 117.28 (s, *C*N); 170.14 (s, *C*=O). $C_{11}H_{20}NO_6P$: requires C 45.05, H 6.87, N 4.78; found C 45.27, H 6.82, N 4.81.

4-(Diethoxyphosphoryl)-4-(diethoxyphosphoryloxy)butyric acid ethyl ester (32). To a solution of phosphonate **21** (0.80 g, 3.0 mmol) and diethyl phosphite (0.52 ml, 3.0 mmol) in ethanol (10 ml), a catalytic amount of sodium ethoxide (15 mg) was added and the mixture was stirred for 0.5 h at room temperature. Water (5 ml) was added and ethanol was evaporated under reduced pressure. The residue was extracted with methylene chloride (3 × 15 ml). The combined organic layers were washed with saturated NaCl solution (5 ml) then dried (MgSO$_4$) and evaporated under reduced pressure. The residue was chromatographed (CHCl$_3$–acetone 90 : 10, R_f = 0.20) to give the ester **32** as a colourless oil (0.97 g, 80%); ν_{max} 1748, 1226, 1024; δ_P (CDCl$_3$) −0.67 (d, $^3J_{PP}$ = 22.2 Hz); 19.51 (d, $^3J_{PP}$ = 22.2 Hz); δ_H (CDCl$_3$) 1.26 (t, $^3J_{HH}$ = 7.0 Hz, 3H, C*H*$_3$CH$_2$O); 1.35 (t, $^3J_{HH}$ = 7.0 Hz, 6H, 2 × C*H*$_3$CH$_2$OP); 1.36 (t, $^3J_{HH}$ = 7.0 Hz, 6H, 2 × C*H*$_3$CH$_2$OP); 2.07–2.19 (m, 1H, C*H*H); 2.23–2.36 (m, 1H, CH*H*); 2.56–2.64 (m, 2H, C*H*$_2$); 4.15 (dq, $^3J_{PH}$ = $^3J_{HH}$ = 7.0 Hz, 8H, 4 × C*H*$_2$OP); 4.20 (q, 2H, $^3J_{HH}$ = 7.0 Hz, C*H*$_2$O), 4.69 (dddd, $^2J_{PH}$ = 15.2 Hz, $^3J_{PH}$ = 10.5 Hz, $^3J_{HH}$ = 8.0 Hz $^3J_{HH}$ = 4.7 Hz, 1H, C*H*O); δ_C (CDCl$_3$) 13.81 (s, *C*H$_3$CH$_2$O); 15.66 (d, $^3J_{PC}$ = 7.0 Hz, *C*H$_3$CH$_2$OP); 15.68 (d, $^3J_{PC}$ = 6.9 Hz, *C*H$_3$CH$_2$OP); 16.05 (d, $^3J_{PC}$ = 5.6 Hz, *C*H$_3$CH$_2$OP); 16.08 (d, $^3J_{PC}$ = 5.6 Hz, *C*H$_3$CH$_2$OP); 25.95 (dd, $^3J_{PC}$ = 7.2 Hz, $^4J_{PC}$ = 4.3 Hz, *C*H$_2$); 29.38 (d, $^2J_{PC}$ = 41.7 Hz, *C*H$_2$); 60.12 (s, *C*H$_2$O); 62.58 (s, 2 × *C*H$_2$OP); 62.97 (s, 2 × *C*H$_2$OP); 71.65 (dd, $^1J_{PC}$ = 171.2 Hz, $^2J_{PC}$ = 7.2 Hz, *C*HO); 172.05 (s, *C*=O). $C_{14}H_{30}O_9P_2$: requires C 41.59, H 7.48; found C 41.68, H 7.44.

General procedure for the preparation of cyclopropanecarboxylates 31 and 33. To a suspension of sodium hydride (0.048 g, 2.0 mmol) in tetrahydrofuran (10 ml), phosphate **30** or **32** (2.0 mmol) was added and the resulting mixture was stirred for 0.5 h at room temperature and then heated at reflux for 5 h. Saturated NaCl solution (5 ml) was added and tetrahydrofuran was evaporated under reduced pressure. The residue was extracted with methylene chloride (3 × 15 ml). The combined organic layers were dried (MgSO$_4$) and then evaporated under pressure to give a crude product, which was purified by column chromatography.

***Trans*-2-Cyanocyclopropanecarboxylic acid ethyl ester (31)[22].** Purification (CHCl$_3$, R_f = 0.46) gave the ester **31** as a colourless oil (0.20 g, 68%); δ_H (CDCl$_3$) 1.26 (t, $^3J_{HH}$ = 7.0 Hz, 3H, C*H*$_3$CH$_2$O); 1.42 (ddd, $^3J_{HH}$ = 9.0 Hz, $^3J_{HH}$ = 6.0 Hz, $^2J_{HH}$ = 4.5 Hz, 1H, CH*H*); 1.50 (ddd, $^3J_{HH}$ = 8.7 Hz, $^3J_{HH}$ = 6.2 Hz, $^2J_{HH}$ = 4.5 Hz, 1H, C*H*H); 1.94 (ddd, $^3J_{HH}$ = 9.0 Hz, $^3J_{HH}$ = 6.2 Hz, $^3J_{HH}$ = 4.7 Hz, 1H, C*H*); 2.25 (ddd, $^3J_{HH}$ = 8.7 Hz, $^3J_{HH}$ = 6.0 Hz, $^3J_{HH}$ = 4.7 Hz, 1H, C*H*); 4.18 (q, $^3J_{HH}$ = 7.0 Hz, 2H, C*H*$_2$O).

***Trans*-2-(Diethoxyphosphoryl)cyclopropanecarboxylic acid ethyl ester (33)[23].** Purification (CHCl$_3$–acetone 90 : 10, R_f = 0.24) gave the ester **33** as a colourless oil (0.35 g, 70%); δ_P (CDCl$_3$) 22.64; δ_H (CDCl$_3$) 1.00–1.11 (m, 2H, C*H*$_2$-C3); 1.12 (t, $^3J_{HH}$ = 7.0 Hz, 3H, C*H*$_3$CH$_2$O); 1.37 (td, $^3J_{HH}$ = 7.0 Hz, $^4J_{PH}$ = 0.5 Hz, 6H, 2 × CH$_2$OP); 1.54 (dddd, $^3J_{PH}$ = 15.2 Hz, $^3J_{HH}$ = 10.0 Hz, $^3J_{HH}$ = 6.2 Hz, $^3J_{HH}$ = 6.0 Hz, 1H, C*H*); 2.10 (dddd, $^2J_{PH}$ = 20.0 Hz, $^3J_{HH}$ = 9.5 Hz, $^3J_{HH}$ = 6.5 Hz, $^3J_{HH}$ = 6.0 Hz, 1H, C*H*); 4.09 (q, $^3J_{HH}$ = 7.0 Hz, 2H, C*H*$_2$O); 4.12 (dq, $^3J_{PH}$ = $^3J_{HH}$ = 7.00 Hz, 2H, C*H*$_2$OP); 4.13 (dq, $^3J_{PH}$ = $^3J_{HH}$ = 7.0 Hz, 2H, C*H*$_2$OP).

(*E*)-5-(Diethoxyphosphoryl)hex-2-enedioic acid diethyl ester (35) and 2-[(diethoxyphosphoryl)ethoxycarbonylmethyl]cyclopropanecarboxylic acid ethyl ester (36). To a suspension of sodium hydride (0.072 g, 3.0 mmol) in tetrahydrofuran (10 ml), triethyl phosphonoacetate (0.6 ml, 3.0 mmol) was added at room temperature and the mixture was stirred for 0.5 h. Then phosphate **21** (0.8 g, 3.0 mmol) was added and the resulting mixture was heated at reflux for 5 h. Water (10 ml) was added and tetrahydrofuran was evaporated under reduced pressure. The residue was extracted with methylene chloride (4 × 15 ml) and dried (MgSO$_4$). Evaporation of the solvent afforded crude products **35** and **36**, which were separated by column chromatography using ethyl acetate as eluent.

Compound 35. Yield (0.1 g, 13%); colourless oil; (R_f = 0.49); ν_{max} 1748, 1720, 1648, 1226, 1032; δ_P (CDCl$_3$) 21.51; δ_H (CDCl$_3$) 1.27 (td, $^3J_{HH}$ = 7.0 Hz, $^4J_{PH}$ = 1.0 Hz, 3H, C*H*$_3$CH$_2$OP); 1.31 (td, $^3J_{HH}$ = 7.0 Hz, $^4J_{PH}$ = 1.0 Hz, 3H, C*H*$_3$CH$_2$OP); 1.34 (t, $^3J_{HH}$ = 7.0 Hz, 3H, C*H*$_3$CH$_2$O); 1.35 (t, $^3J_{HH}$ = 7.0 Hz, 3H, C*H*$_3$CH$_2$O); 2.76 (dddd, $^3J_{PH}$ = 11.5 Hz, $^3J_{HH}$ = 7.0 Hz, $^3J_{HH}$ = 4.0 Hz, $^4J_{HH}$ = 1.5 Hz, 1H, C*H*H); 2.82 (dddd, $^3J_{HH}$ = 10.5 Hz, $^3J_{PH}$ = 8.5 Hz, $^3J_{HH}$ = 7.0 Hz, $^4J_{HH}$ = 1.50 Hz, 1H, CH*H*); 3.09 (ddd, $^2J_{PH}$ = 22.7 Hz, $^3J_{HH}$ = 10.5 Hz, $^3J_{HH}$ = 4.0 Hz, 1H, C*H*); 4.10–4.26 (m, 8H, 2 × C*H*$_2$O, 2 × C*H*$_2$OP); 5.89 (dt, $^3J_{HH}$ = 15.5 Hz,

$^4J_{HH}$ = 1.5 Hz, 1H, C*H*); 6.86 (dt, $^3J_{HH}$ = 15.5 Hz, $^3J_{HH}$ = 7.0 Hz, 1H, C*H*); δ_C ($CDCl_3$) 14.03 (s, *C*H_3CH$_2$O); 14.15 (s, *C*H_3CH$_2$O); 16.28 (d, $^3J_{PC}$ = 5.7 Hz, 2 × *C*H_3CH$_2$OP); 29.34 (d, $^2J_{PC}$ = 3.8 Hz, *C*H$_2$); 44.38 (d, $^1J_{PC}$ = 131.3 Hz, *C*HP); 60.31 (s, *C*H$_2$O); 61.65 (s, *C*H$_2$O); 62.84 (d, $^2J_{PC}$ = 7.15 Hz, *C*H$_2$OP); 62.97 (d, $^2J_{PC}$ = 7.2 Hz, *C*H$_2$OP); 123.45 (s, *C*H); 144.21 (d, $^3J_{PC}$ = 15.7 Hz, *C*H); 165.96 (s, *C*=O); 167.99 (d, $^2J_{PC}$ = 4.7 Hz, *C*=O). $C_{14}H_{25}O_7P$: requires C 50.00, H 7.49; found C 49.77, H 7.44.

Compound 36. Yield (0.13 g, 13%); colourless oil; (R_f = 0.63); ν_{max} 1764, 1724, 1220, 1024; δ_P ($CDCl_3$) 23.16; δ_H ($CDCl_3$) 1.18 (td, $^3J_{HH}$ = 7.0 Hz, $^4J_{PH}$ = 1.2 Hz, 3H, C*H*$_3$CH$_2$OP); 1.20–1.38 (m, 12H, 2 × C*H*$_3$CH$_2$O, C*H*$_3$CH$_2$OP, C*H*$_2$, C*H*); 2.24 (ddddd, $^3J_{HH}$ = 11.0 Hz, $^3J_{HH}$ = 10.5 Hz, $^3J_{PH}$ = 7.0 Hz, $^3J_{HH}$ = 6.0 Hz, $^3J_{HH}$ = 5.0 Hz, 1H, C*H*); 3.12 (dd, $^2J_{PH}$ = 23.2 Hz, $^3J_{HH}$ = 10.5 Hz, 1H, C*H*); 4.11–4.24 (m, 8H, 2 × C*H*$_2$O, 2 × C*H*$_2$OP); δ_C ($CDCl_3$) 14.03 (s, *C*H_3CH$_2$O); 15.13 (s, *C*H_3CH$_2$O); 16.28 (d, $^3J_{PC}$ = 5.7 Hz, 2 × *C*H_3CH$_2$OP); 21.10 (d, $^3J_{PC}$ = 2.6 Hz, *C*H2); 28.95 (s, *C*H); 30.88 (d, $^2J_{PC}$ = 3.0 Hz, P*C*H); 41.41 (d, $^1J_{PC}$ = 131.3 Hz, *C*HP); 61.28 (s, *C*H$_2$O); 62.14 (s, *C*H$_2$O); 62.63 (d, $^2J_{PC}$ = 6.2 Hz, *C*H$_2$OP); 62.95 (d, $^2J_{PC}$ = 6.1 Hz, *C*H$_2$OP); 168.92 (d, $^2J_{PC}$ = 3.1 Hz, *C*=O); 175.14 (s, *C*=O). $C_{14}H_{25}O_7P$: requires C 50.00, H 7.49; found C 50.19, H 7.45.

Crystal structure determination of 1-benzyl-2-methylcyclopropanecarboxylate anion derived from the ester 7h. $C_{12}H_{13}NO_2 \cdot C_{12}H_{24}N$, M_w = 371.55, colourless crystal 0.40 × 0.20 × 0.10 mm, triclinic, a = 10.2817(1), b = 10.6027(1), c = 11.7395(2) Å, α = 64.164(1), β = 86.195(1), γ = 73.578(1)°, V = 1102.46(2) Å^3, space group $P\bar{1}$, Z = 2, ρ_{calc} = 1.20 g cm^{-3}, μ = 0.537 mm^{-1}, $F(000)$ = 408, semi-empirical absorption correction based on multiple scanned equivalent reflections (0.827 < T < 0.943), λ(Cu-Kα) = 1.54178 Å, T = 293 K, ω scans, 12 592 reflections collected ($\pm h$, $\pm k$, $\pm l$), $2\theta_{max}$ = 142°, 4052 unique reflections (R_{int} = 0.014), 392 refined parameters, refinement on F^2, final R = 0.048 for 3765 observed reflections [$F_o > 4\sigma(F_o)$], R_{all} = 0.050, $wR_{all}(F^2)$ = 0.140, residual electron density $\Delta\rho_{max}$ = 0.19 $\Delta\rho_{min}$ = −0.22 e Å^{-3}, all hydrogen atoms refined with individual isotropic temperature factors. X-Ray data were collected with a Bruker SMART APEX CCD area detector diffractometer. Computer programs used: data collection: SMART APEX,[24] data reduction: SAINT-Plus,[25] absorption correction: SADABS,[26] structure solution, refinement and molecular graphics: SHELXTL.[27] CCDC reference number 653900. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b712145h

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