Intramolecular [2 + 2] Cycloadditions of Alkoxyketenes and Alkoxyketeniminium Salts

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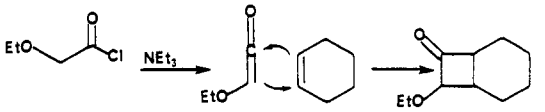
(Alkenyloxy)ketenes, prepared from the acid chloride by treatment with triethylamine in benzene at reflux, undergo facile intramolecular [2 + 2] cycloaddition to give polycyclic cyclobutanones. Electronic effects of the alkyl substituents on the double bond control the regiochemistry of the cycloaddition. Alkenes in which the internal carbon is more highly substituted react to give bicyclo[3.2.0]heptanones or bicyclo[4.2.0]octanones. Alkenes in which the terminal carbon is more highly substituted react to give bicyclo[3.1.1]heptanones or bicyclo[4.1.1]octanones. Mono- and 1,2-disubstituted alkenes are not nucleophilic enough to react. (Alkenyloxy)keteniminium salts, prepared from the dimethylamide by treatment with triflic anhydride and collidine in benzene at reflux, undergo facile intramolecular [2 + 2] cycloaddition to mono- and 1,1- and 1,2-disubstituted alkenes to give, after hydrolysis, polycyclic cyclobutanones. Other classes of alkenes give Friedel–Crafts products. The 25 cases examined indicate the scope and limitations of intramolecular [2 + 2] cycloadditions of ketenes to alkenes as a synthetic method. Baeyer–Villiger oxidation of the cycloadducts gives furofuranones of a type closely related to the furofurans present in insect antifeedants and aflatoxins.

The stereospecific [2 + 2] cycloaddition of ketenes to alkenes is a valuable method for the synthesis of cyclobutanones and compounds that can be derived from them.[2] It is one of the few general methods for the carbofunctionalization of alkenes. Although numerous isolated examples of intramolecular [2 + 2] cycloaddition of ketenes to alkenes are known,[3] the reaction has not been developed into a general synthetic method.[4,5] Remarkably, of the numerous papers reporting an intramolecular [2 + 2] cycloaddition of a ketene,[3] only those of Becker[3j,r,v] report more than a single example.

The intramolecular reaction promises to extend the scope of the cycloaddition to less reactive alkenes and ketenes. More importantly,[14] it offers an efficient route to complex polycyclic compounds that are not available by other methods. The intramolecular nature of the reaction should also control the stereo- and regioselectivity of the reaction in a way not possible in intermolecular reactions.

Alkoxyketenes were chosen for initial exploratory work for several reasons. Strausz and Do Minh reported that ethoxyketene, prepared from ethoxyacetyl chloride and NEt_3, adds to alkenes to give 2-ethoxycyclobutanones in 30–50% yield[6] (eq 1). While these yields appear to be



(1)

acceptable, they are achieved by using excess alkene as the solvent. The related intramolecular reactions should proceed in good yield since the intramolecularity of the reaction is equivalent to using the alkene as solvent in an intermolecular reaction. Strausz and Do Minh's results do indicate that alkoxyketenes are more reactive than alkylketenes, which do not react with alkenes in intermolecular reactions. In addition, the (alkenyloxy)acetic acids necessary for the preparation of the ketenes are readily available through the Williamson ether synthesis using bromoacetic acid and unsaturated alcohols. This allowed us to prepare numerous ketene precursors by a common single-step sequence. Furthermore, the presence of the oxygen simplifies the NMR spectra of the cycloadducts. The oxygen replaces a CH_2 group and shifts adjacent protons out of the envelope at δ 1–2. This has been invaluable as an aid in assigning the structure of the adducts (vide infra). Finally, Baeyer–Villiger oxidation of the cycloadducts gives furofuranones of a type closely related to the furofurans present in insect antifeedants and aflatoxins.

Results and Discussion

Alkoxyketenes. The requisite (alkenyloxy)acetic acids were prepared in 70–90% yield by reaction of an unsaturated alcohol with bromoacetic acid and 2 equiv of sodium hydride in THF at reflux.[7] The acid was converted to the acid chloride by treatment with excess oxalyl chloride in benzene at reflux. A 0.04 M solution of the acid chloride and 1.1–1.5 equiv of NEt_3 in benzene was heated at reflux

(1) Fellow of the Alfred P. Sloan Foundation 1979–1983; Dreyfus-Teacher Scholar 1982–1987.

(2) (a) Brady, W. T. *Tetrahedron* **1981**, *37*, 2949. (b) Ghosez, L. "Stereoselective Synthesis of Natural Products"; Bartmann, W., Winterfeldt, E., Eds.; Excerpta Medica: Amsterdam, Oxford, 1979; pp 93–105. (c) Ghosez, L.; O'Donnell, M. J. "Pericyclic Reactions"; Marchand, A. P., Lehr, R. E., Eds.; Academic Press: New York, 1977; Vol. II, pp 79–140.

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(5) For a complementary study of intramolecular cycloadditions of ketenes and keteniminium salts see: Marko, I.; Ronsmans, B.; Hesbain-Frisque, A.-M.; Dumas, D.; Ghosez, L.; Ernst, B.; Greuer, H. *J. Am. Chem. Soc.* **1985**, *107*, 2192.

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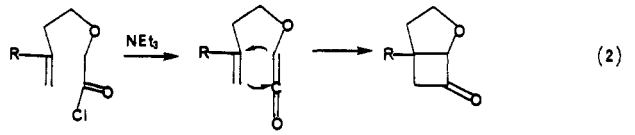
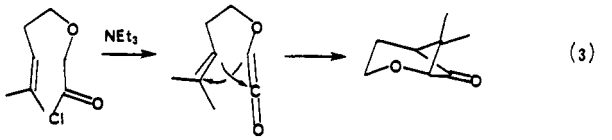
for 1.5–24 h to give the ketene, which reacted to give the cyclobutanone. The results are shown in Table I.

Remarkably, the results indicate that the electronic effects of the alkyl substituents on the double bond control the regiochemistry of the cycloaddition. Although the cycloaddition is concerted, leading bond formation occurs between the electrophilic carbonyl carbon of the ketene and the less substituted end of the alkene, leading to a transition state with partial positive charge on the more substituted carbon of the alkene.[2c] Alkenes in which the internal carbon is more highly substituted (entries 1–7, 11, and 12) react to give bicyclo[3.2.0]heptanones or bicyclo[4.2.0]octanones (see eq 2). Alkenes in which the terminal carbon is more highly substituted (entries 9 and 10) react to give bicyclo[3.1.1]heptanones or bicyclo[4.1.1]octanones (see eq 3). The formation of bridged ring compounds has not been observed previously in intramolecular cycloadditions of ketenes.



(2)



(3)

The reactivity of alkenes with various substitution patterns can be understood by considering that leading bond formation occurs between the electrophilic carbonyl carbon of the ketene and the least substituted end of the alkene. Therefore, alkenes with the substitution pattern of entries 1–3, 5, 6, and 11 (Table I) are the most reactive since bond formation occurs at a sterically unhindered unsubstituted carbon and any positive charge in the transition state is at a tertiary carbon. The styrene of entry 7 is also very reactive since any positive charge in the transition state is at a benzylic carbon. The monosubstituted alkene shown in entry 4 gives only a 16% yield of cycloadduct since any positive charge must be at a secondary carbon. 1,2-Disubstituted alkenes such as that in entry 13 in which cycloaddition is hindered by the ethyl substituent on the double bond give no cycloadduct.

The cycloaddition of the cyclohexylethoxy ketene (entry 12) gives a 5% yield of **32** in addition to a 58% yield of the adduct **31**, which is expected on electronic grounds. Competing steric effects favor the formation of **32** since leading bond formation at the carbonyl group gives initially a six-membered ring in the formation of **32** but a seven-membered ring in the formation of the electronically favored adduct **31**. Similar competing effects have been noted in intramolecular cycloadditions of nitrones[8] and are more clearly seen in the reactions of alkoxyketeniminium salts (vide infra). The cycloaddition shown in entry 12 differs from others with a disubstituted internal carbon since the terminal carbon bears an alkyl substituent, making electronic effects less significant than in entries 1–3, 5, 6, and 11.

Allylic alkoxyketenes would have to give an oxabicyclo[2.2.0]hexane or an oxabicyclo[2.1.1]hexanone. Both of these systems are sufficiently strained that they probably cannot be isolated from the reversible cycloaddition of a ketene. We have, however, obtained evidence for the formation of an oxabicyclo[2.1.1]hexanone as a transient

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Table I. Intramolecular [2 + 2] Cycloaddition Reactions of Ketenes Derived from (Alkenyloxy)acetic Acids

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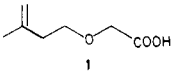
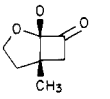
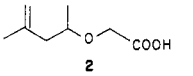
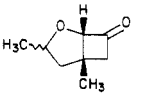
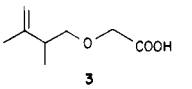
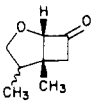
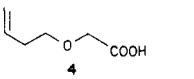
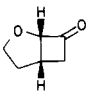
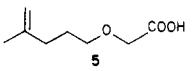
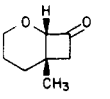
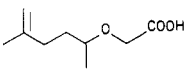
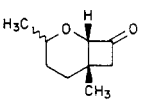
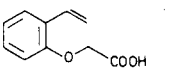
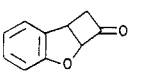
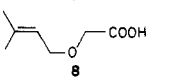
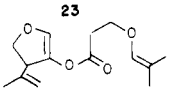
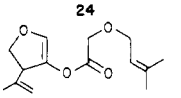
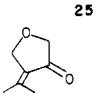
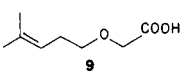
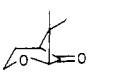
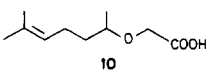
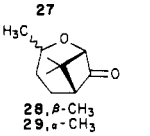
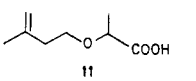
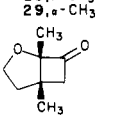
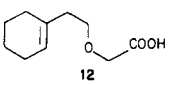
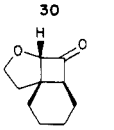
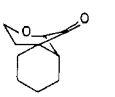
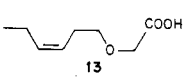
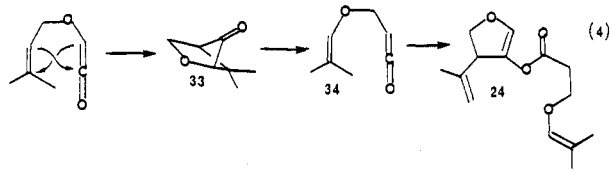
1	 1	 14	72
2	 2	 15, β-CH_3 16, α-CH_3	7 66
3	 3	 17, β-CH_3 18, α-CH_3	28 35
4	 4	 19	16
5	 5	 20	62
6	 6	 21, 22	58 (3:2)
7	 7	 23	70
8	 8	 24	16
		 25	10
		 26	22
9	 9	 27	52
10	 10	 28, β-CH_3 29, α-CH_3	13 17
11	 11	 30	50
12	 12	 31	58
		 32	5
13	 13	—	—

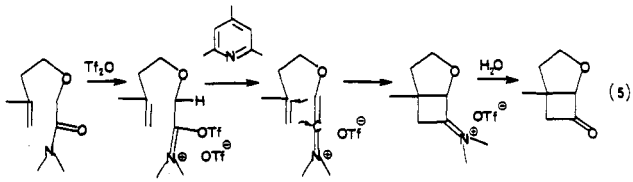
intermediate (entry 8). (Prenyloxy)acetyl chloride reacts with NEt_3 to give the Friedel–Crafts adduct **26** and the related dimers **24** and **25**. Dimer **24** is of particular interest since the oxygen and methylene groups have switched positions in the chain. The only plausible mechanism for this that we are aware of is cycloaddition of the ketene derived from **8** to give **33** folloed by cycloreversion to give the isomeric ketene **34** that then reacts with another molecule of ketene or acid chloride to give **24** (see eq 4). The result indicates that formation of bicyclo[2.1.1]hexanones is mechanistically feasible, but thermodynamically unfavored.



The effects of base, solvent, and temperature were examined briefly in the cyclization of the acid chloride derived from **1**. Low yields of **14** were obtained in benzene at 25 °C or in CH_2Cl_2 at reflux. Low yields were also obtained with DBU or diisopropylethylamine in benzene at reflux. These results are consistent with other studies of ketene generation and cycloaddition that indicate that the amine hydrochlorides catalyze the decomposition of ketenes.[9] Cycloaddition will be favored by the use of a nonpolar solvent and an amine containing a small number of carbons such as NEt_3, which forms a hydrochloride that is insoluble in benzene at reflux. We have not studied the effect of concentration on the yield of these reactions. In related all-carbon systems we have found that only slight decreases in yield occur on increasing the concentration to 0.2 M.[10]

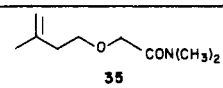
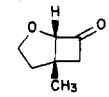
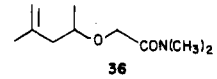
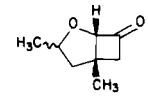
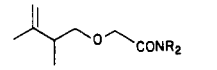
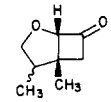
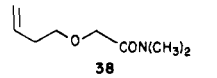
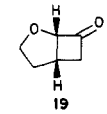
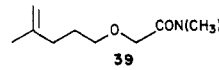
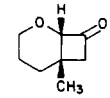
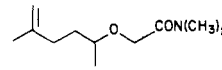
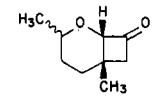
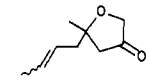
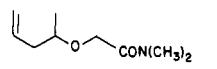
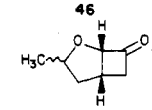
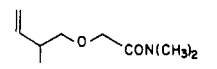
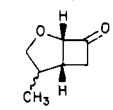
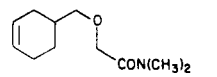
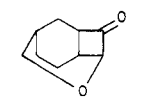
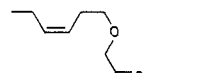
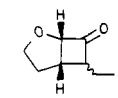
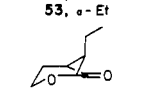
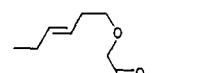
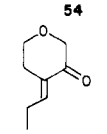
Alkoxyketeniminium Salts. The cycloaddition of keteniminium salts was developed by Ghosez and coworkers as a more electrophilic alternative to ketenes that will react with less nucleophilic alkenes.[5,11] The intramolecular cycloaddition of keteniminium salts and alkenes should therefore complement the ketene cycloaddition that failed with mono- and 1,2-disubstituted alkenes. The use of keteniminium salts, instead of ketenes, with reactive alkenes may lead to different mixtures of stereoisomers because of the bulk of the iminium salt and the change from a concerted to a stepwise mechanism.

Treatment of an unsaturated alcohol with 1 equiv of sodium hydride and bromo-*N*,*N*-dimethylacetamide in THF gave the requisite (alkenyloxy)-*N*,*N*-dimethylacetamide in 60–90% yield. Treatment of the amide (~0.04 M in benzene at reflux) with 1 equiv of triflic anhydride (Tf_2O) and 1 equiv of collidine by the procedure of Ghosez et al.[11b] gave the keteniminium salt that added to the double bond to give, after hydrolysis, the cyclobutanone (see eq 5).



(9) Brady, W. T.; Waters, O. H. *J. Org. Chem.* **1967**, *32*, 3703 and ref 10 and 11 therein.
(10) Kulkarni, J. S.; Snider, B. B. *J. Org. Chem.* **1985**, *50*, 2809.
(11) (a) Ghosez, L.; Marchand-Brynaert, J. "Iminium Salts in Organic Chemistry", Part 1; Boöhme, J., Viehe, H. G., Eds.; Wiley: New York, 1976; pp 421–532. (b) Falmagne, J.-B.; Escudero, J.; Taleb-Sahraoui, S.; Ghosez, L. *Angew. Chem., Int. Ed. Engl.* **1981**, *20*, 879.

Table II. Intramolecular [2 + 2] Cycloaddition Reactions of Keteniminium Salts Derived from (Alkenyloxy)acetamides

entry	(alkenyloxy)acetamide	cyclobutanone	yield,[a] %
1	 **35**	 **14**	81
2	 **36**	 **15**, β-CH_3 **16**, α-CH_3	65 9
3	 **37a**, R = Me **b**, R = Et	 **17**, β-CH_3 **18**, α-CH_3	(a) 15, (b) 10 (a) 62, (b) 73
4	 **38**	 **19**	79
5	 **39**	 **20**	33
6	 **40**	 **21**, **22**	16
		 **46**	19 (7:3 *E*/*Z*)
7	 **41**	 **47**, β-CH_3 **48**, α-CH_3	53 5
8	 **42**	 **49**, β-CH_3 **50**, α-CH_3	27 33
9	 **43**	 **51**	24
10	 **44**	 **52**, β-Et **53**, α-Et	33 7
		 **54**	9
11	 **45**	 **55**	64

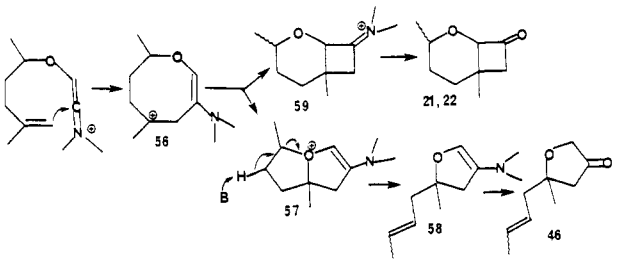
The results shown in Table II clearly indicate that there are both advantages and disadvantages to the use of keteniminium salts. Alkoxyketeniminium salts do undergo intramolecular cycloaddition reactions with monosubstituted and cis 1,2-disubstituted alkenes in moderate to good yield (entries 4 and 7–11), as compared to the ketene series

in which the monosubstituted alkene reacts in low yield and the cis 1,2-disubstituted alkene does not react.

The stereochemical differences between the keteniminium salt and ketene cycloadditions are most clearly apparent by comparison of entries 2 and 3 in Tables I and II. Entry 2 in Table I leads to a 9:1 mixture of α- and β-methyl isomers. Entry 2 in Table II leads to a 1:7 mixture of α- and β-methyl isomers. The complementary stereochemistry of the ketenes and keteniminium salt cyclizations is attractive synthetically. Unfortunately, we have not been able to explain the origin of the selectivity in either case. The problem is more complex than it first appears, since either the bulk of the iminium salt or the change to a stepwise mechanism, or both, could be responsible for the change in the stereoselectivity. Steric interactions with the methyl substituent on the double bond are probably not important since **16** and **48** are formed with similar stereoselectivity.

The stereoselectivity in the formation of **18** (entry 3a, Table II) is only moderate. This still compares favorably to the ketene analogue (entry 3, Table I), which is almost stereorandom. Ghosez has shown that modification of the substituents on nitrogen can be a powerful tool for the control of reactivity or stereoselectivity.[11a,12a] We have briefly examined the possibility of improving the stereoselectivity by modification of the nitrogen substituents. Use of the diethylketeniminium salt (entry 3b, Table II) improves the selectivity from 4:1 to 7:1.

The use of keteniminium salts instead of ketenes does have some disadvantages and limitations. The formation of oxabicyclo[4.2.0]octanones proceeds in much lower yield than the corresponding ketene cyclizations (Table II, entries 5 and 6; Table I, entries 5 and 6). The isolation of **46** from the cyclization of the salt derived from **40** provides a mechanistic rationale for the formation of side products. The stepwise keteniminium cyclization proceeds through **56**, which can now cyclize to **57** in addition to the desired cyclobutanone precursor **59**. The oxonium salt **57** should undergo facile base-catalyzed E_2 elimination to give **58**, which will give **46** after hydrolysis. It is likely that related products, which were not characterized, are responsible for the low yield in entry 5.



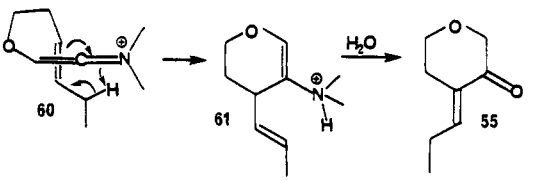
The reaction of the keteniminium salt **60** derived from **45** (entry 11) indicates a limitation of keteneiminium salts that is well-known in intermolecular reactions. 1,1-Disubstituted alkenes give a low yield of cyclobutanone.[11a] The major product is the Friedel–Crafts adduct. In keteniminium salt **60** the allylic hydrogen is held in close proximity to the nitrogen so that ene reaction can occur readily to give **61**, which gives the Friedel–Crafts adduct **55** on hydrolysis. This competing ene reaction cannot occur with monosubstituted or cis 1,2-disubstituted alkenes and is not a significant side reaction with *gem*-disubstituted alkenes, presumably because of steric constraints.

Table III. Change in Product Ratios from the Cyclization of 44 in 1,2-Dichloroethane[a] as a Function of Time and Temperature

reactn time, h	temp, °C	rel amt[b] 44	52	53	54
17	50	45	0	5	49
43	50	26	0	11	63
65	50	26	trace	16	58
108	50	31	trace	19	50
3.5	85	trace	0	28	72
7.5	85	trace	7	45	48
12.3	85	trace	16	55	29
22.0	85	trace	38	53	9
54.0	85	trace	53	42	5
73.0	85	trace	76	24	0
95.0	85	trace	85	15	0

[a] The reaction was carried out as described in the Experimental Section except that 1,2-dichloroethane was used as a solvent, which resulted in a homogeneous reaction mixture. [b] Reaction aliquots were hydrolyzed as described in the Experimental Section. The product ratios were determined by NMR analysis of the CCl_4 extracts.

Keteniminium salts corresponding to entries **9**, **10**, and 12 of Table I were not examined since the formation of monocyclic enones corresponding to **55** was anticipated.



The cyclizations of cis 1,2-disubstituted (alkenyloxy)ketenes (Table II, entries 9 and 10) provide a wealth of mechanistic information. Since the cycloaddition of keteniminium salts with symmetrical alkenes has no electronic effects, any regioselectivity is a result of connectivity effects. The (cyclohexenylmethoxy)keteniminium salt derived from **43** gives a single adduct **51** that results from the expected leading bond formation to give the kinetically preferred seven- rather than eight-membered ring.

The cyclization of (*cis*-3-hexenyloxy)keteniminium salt **44a**, derived from **44**, is complicated by extensive rearrangement and isomerization. Since the keteniminium salts and cycloadducts are not soluble in benzene, the cyclization of **44a** was examined in 1,2-dichloroethane at 50 and 80 °C. The results of these cyclization reactions are shown in Table III. The kinetic product **62**, which again results from kinetically preferred formation of a six- rather than a seven-membered ring, is obtained selectively after short reaction times at 50 °C. At longer reaction times **62** is slowly converted to **64**. At 85 °C, **62** is rapidly converted to **64**, which is more slowly converted to the thermodynamic product **65**. The reaction conditions can be adjusted to obtain either **52**, **53**, or **54** as the major product after hydrolysis.

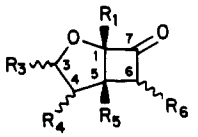
The isomerization of **54** to **53** could occur by cycloreversion of the iminium salt **62** and readdition, a process known to be facile at 65 °C in related ketene systems.[13] A more likely mechanism involves isomerization of **62** to the oxygen-stabilized cyclopropylcarbinyl cation **63**, which can then isomerize to **64**. This process is well precedented in systems that should be less reactive than **62**.[13,14] Finally,

(12) (a) Saimoto, H.; Houghe, C.; Hesbain-Frisque, A.-M.; Mockel, A.; Ghosez, L. *Tetrahedron Lett.* **1983**, *24*, 2251. (b) Houge, C.; Frisque-Hesbain, A.-M.; Mockel, A.; Ghosez, L.; Declercq, J. P.; Germain, G.; Van Meerssche, M. *J. Am. Chem. Soc.* **1982**, *104*, 2920.

(13) Erman, W. F.; Treptow, R. S.; Bazukis, P.; Wenkert, E. *J. Am. Chem. Soc.* **1971**, *93*, 657.

(14) Tsuda, Y.; Isobe, K.; Tanno, T.; Ukai, A. *Chem. Pharm. Bull.* **1975**, *23*, 1775.

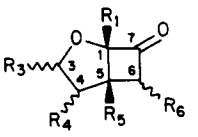
Table IV. Proton Chemical Shifts of 2-Oxabicyclo[3.2.0]heptan-7-ones[a]



	chem shifts, δ									
	H_1	$H_{3\alpha}$	$H_{3\beta}$	$H_{4\alpha}$	$H_{4\beta}$	H_5	$H_{6\alpha}$	$H_{6\beta}$	Me (C_5)	other (J, Hz)
14, R_5 = Me	4.53	3.78	4.21	2.05	1.90	Me	2.74	2.88	1.56	
15, R_5 = Me, R_3 = β-Me	4.58	4.15	Me	2.15	1.51	Me	2.78	2.88	1.54	1.36 (5.5)
16, R_5 = Me, R_3 = α-Me	4.55	Me	4.47	1.69	2.19	Me	2.81	2.90	1.53	1.29 (6.5)
17, R_5 = Me, R_4 = β-Me	4.51	3.84	4.04	2.21	Me	Me	2.75	2.81	1.40	1.04 (7.2)
18, R_5 = Me, R_4 = α-Me	4.54	3.38	4.17	Me	2.17	Me	2.56	2.89	1.45	1.01 (6.7)
19	5.07	3.76	4.23	1.91	2.07	3.08	2.53	3.17		
47, R_3 = β-Me	5.08	4.10	Me	2.00	1.66	3.10	2.55	3.15		1.33 (5.9)
48, R_3 = α-Me	5.03	Me	4.40	1.50	2.51	3.13	2.76	3.17		1.31 (6.3)
49, R_4 = β-Me	5.10	3.91	3.87	2.27	Me	2.70	2.58	3.17		1.08 (6.7)
50, R_4 = α-Me	5.08	3.35	4.14	Me	2.50	3.08	2.78	2.91		1.08 (6.7)
52, R_6 = β-Et	5.01	3.76	4.23	1.94	2.07	2.76	2.64	Et		*b*
53, R_6 = α-Et	5.15	3.61	4.18	⟨2.01-1.9⟩		3.17	Et	3.09		*c*
30, R_1 = R_5 = Me	Me	3.73	4.15	2.07	1.89	Me	2.73	2.81	1.35	1.24
31, R_5,R_6 = $(CH_2)_4$	4.81	3.83	4.19	2.05	1.88		2.80			1.9-1.3

[a] R = H unless otherwise specified. [b] δ 1.71 (ddq, 1, J = 7, 14.3, 7.3), 1.61 (ddq, 1, J = 8, 14.3, 7.3), 0.99 (t, 3, J = 7.3). [c] δ 1.67 (ddq, 1, J = 7.5, 13.6, 7.3), 1.38 (ddq, 1, J = 9, 13.6, 7.3), 1.01 (t, 3, J = 7.3).

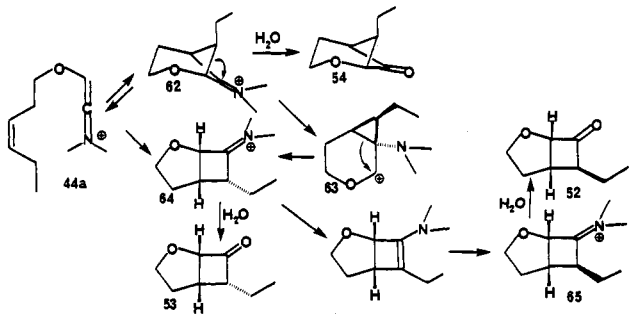
Table V. Proton–Proton Coupling Constants for 2-Oxabicyclo[3.2.0]heptan-7-ones[a]



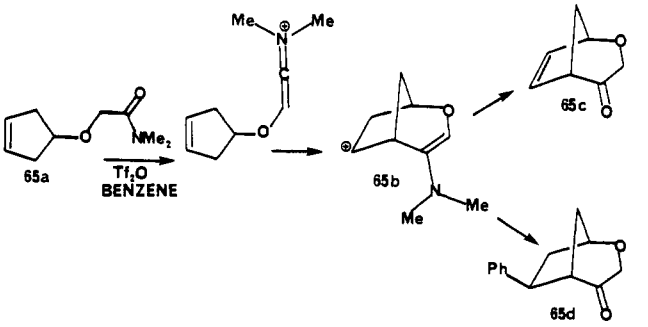
	coupling const, Hz														
	1,5	1,6α	1,6β	3α,3β	3α,4α	3α,4β	3β,4α	3β,4β	4α,4β	4α,5	4β,5	4β,6β	5,6α	5,6β	6α,6β
14, R_5 = Me		2.9	3.7	9.5	5.9	11.2	1.7	8.1	12.3			1.0			18.5
15, R_5 = Me, R_3 = β-Me		3.0	3.8		5.0	12.0			12.2			1.0			19.0
16, R_5 = Me, R_3 = α-Me		2.8	3.0				9.2	5.5	13.0			*b*			17.5
17, R_5 = Me, R_4 = β-Me		2.5	3.5	9.2	3		5.3								18.5
18, R_5 = Me, R_4 = α-Me		4.0	3.0	9.2		11.0		7.0				*b*			19.0
19	6.5	3.3	3.8	9.4	5.5	11.5	1.4	8.2	12.8	0	8.2	0.8	4.3	9.7	18.4
47, R_3 = β-Me	7.3	3.0	3.4		4.9	11.3			12.5	0	8.1	0.9	3.0	10.0	17.2
48, R_3 = α-Me	7.4	3.4	3.4				7.8	6.4	13.1	5.4	9.3	*b*	0	9.3	14.5
49, R_4 = β-Me	6.0	3.1	3.7	9.1	4.9		1.2			<1			4.9	9.8	18.3
50, R_4 = α-Me	7.1	2.7	3.7	9.2		11.6		7.3			*c*	*b*	5.8	9.7	18.5
52, R_6 = β-Et	6.0	3.0		9.0	5.5	11.5	1.0	7.5	13.0	0	7.5		5.0		
53, R_6 = α-Et	7.0		3.0	9.5	6.8	10.7	2.2	7.6	*c*	2.5	8.5	*b*		9	
30, R_1 = R_5 = Me				9.3	5.5	11.8	1.5	7.5	12.2			0.9			18.4
31, R_5, R_6 = $(CH_2)_4$[d]		2.9		9.3	6.4	10.3	2.4	8.3	12.7						*d*

[a] R = H unless otherwise specified. [b] Not seen. [c] Not distinguishable. [d] $J_{6\alpha,CH_2}$ = 7.5, 9.1 Hz.

isomerization of iminium salt **64** to **65** via the enamine is well precedented in adducts from intermolecular keteniminium cycloaddition reactions.[12a]

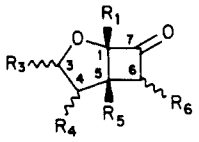


The [2 + 2] cycloaddition reaction of keteniminium salts fails in cases where excessively strained ring systems would be produced. The keteniminium salt derived from **65a** reacts to give **65b**, which loses a proton to give **65c** after hydrolysis in 6% yield and undergoes a Friedel–Crafts reaction with the solvent to give **65d** after hydrolysis in 6% yield.



Structure of the Cycloadducts. The proton and ^{13}C NMR data for the 2-oxabicyclo[3.2.0]heptan-7-ones shown in Tables IV–VI and the proton NMR data for 2-oxabicyclo[3.1.1]heptan-6-ones shown in Table VII allow the unambiguous assignment of structure and stereochemistry. Even though all the coupling constants can be determined,

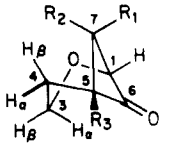
Table VI. Carbon Chemical Shifts and Carbon-Hydrogen Coupling Constants for 2-Oxabicyclo[3.2.0]heptan-7-ones[a]



	chem shifts (δ) and coupling const (Hz)							
	C_1	C_3	C_4	C_5	C_6	C_7	Me (C_5)	others
14, R_5 = Me	97.4 (158)	70.1 (147)	39.4 (133)	39.3	55.1 (135)	210.3	23.8 (126)	
15, R_5 = Me, R_3 = β-Me	97.4 (158)	77.2 (143)	47.1 (131)	40.1	55.5 (135)	211.0	24.2 (126)	19.7 (127)
16, R_5 = Me, R_3 = α-Me	98.0 (154)	81.8 (145)	47.8 (131)	40.05	54.7 (136)	207.8	24.0 (126)	21.1 (126)
17, R_5 = Me, R_4 = β-Me	97.2 (157)	76.7 (146)	42.5 (133)	41.1	56.3 (135)	209.3	18.6 (126)	14.9 (126)
18, R_5 = Me, R_4 = α-Me	97.5 (159)	75.3 (141)[b] (150)	41.9 (129)	42.3	49.4 (135)	209.3	22.3 (126)	9.0 (126)
19	94.0	69.0	32.0	30.7	49.7	210.8		
47, R_3 = β-Me	93.8 (159)	76.0 (144)	39.4 (131)	31.5 (150)	49.8 (136)	211.7		19.4 (127)
48, R_3 = α-Me	94.3 (151)	82.4 (147)	40.7 (131)	31.7 (148)	49.9 (137)	*c*		21.7 (126)
49, R_4 = β-Me	93.7 (159)	75.1 (151)	39.5 (131)	38.2 (145)	49.8 (136)	210.7		19.8 (127)
50, R_4 = α-Me	94.5 (158)	74.3 (146)	35.2 (132)	35.2 (145)	43.5 (135)	210.5		10.4 (126)
52, R_6 = β-Et	91.8	69.1	32.0	37.3	64.7	213.0		22.8, 11.5
53, R_6 = α-Et	91.7	69.9	25.5	34.6	58.9	214.4		16.9, 12.3
30, R_1 = R_5 = Me	99.7	67.4	40.0	41.2	54.5	213.4	20.9	12.8

[a] R = H unless otherwise specified. [b] Two distinct couplings seen. [c] Not seen.

Table VII. Proton Chemical Shifts and Coupling Constants for 2-Oxabicyclo[3.1.1]heptan-6-ones[a]



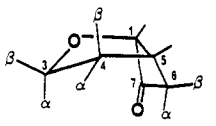
	chem shifts, δ							
	H_1	$H_{3\alpha}$	$H_{3\beta}$	$H_{4\alpha}$	$H_{4\beta}$	H_5	H_7	others
27, R_1 = R_2 = Me	4.06	3.82	4.00	2.08	2.61	2.82		1.29 (R_2), 1.10 (R_1)
32, R_1, R_3 = $(CH_2)_4$	4.34	3.86	4.04	2.03	2.40		1.99	
54, R_2 = Et	4.49	3.82	3.98	1.99	2.56	3.20	~1.8	1.63–1.86 (2), 0.98 (3)

	coupling const, Hz											
	1,5	$1,7_{exo}$	$1,7_{endo}$	3α,3β	3α,4α	3α,4β	3β,4α	3β,4β	4α,4β	4α,5	4β,5	$5,7_{exo}$
27, R_1 = R_2 = Me	7.2			11.4	6.0	10.8	1.2	8.4	12.6	6.0	1.4	
32, R_1, R_3 = $(CH_2)_4$			0	11.2	5.6	11.2	1.8	7.0	12.4			
54, R_2 = Et	7.0	3.5		11.5	5.8	11.5	0	7.5	12.5	6	0	6.5

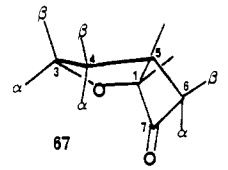
[a] R = H unless otherwise specified.

these assignments are not routine due to the unusual NMR spectra of bicyclo[3.1.1]heptanes. Both $J_{1,5}$ in the *cis*-bicyclo[3.2.0]heptanones and the corresponding $J_{1,5}$ in the bicyclo[3.1.1]heptanones are in the range of 6.0–7.5 Hz.[15] The chemical shifts of the C_5-methyl groups of **14–19** are consistent with related methylbicyclo[3.2.0]heptanones (δ 1.45) but not bicyclo[3.1.1]heptanones (δ 1.04).[16] The chemical shifts and couplings of $H_{6\alpha}$ and $H_{6\beta}$ also require the assigned structures.[17,18]

The conformations and stereochemistry of the C_3- or C_4-methyl-substituted adducts are most easily assigned for **47–50**, which lack the C_5-methyl group. The NMR spectrum of the parent system **19** can be unambiguously assigned. The large coupling between H_5 and $H_{6\beta}$ but not between H_5 and $H_{6\alpha}$ allows the assignment of these protons.[17] More significantly, the small couplings between H_5 and $H_{4\alpha}$ and between $H_{4\alpha}$ and $H_{3\beta}$ require that these dihedral angles be close to 90°. These couplings are only consistent with the assignments indicated in Tables IV and V. Furthermore, they indicate that **19** preferentially adopts the conformation indicated in **66**.



66



67

The stereochemistry of **49** and **50** follows from the similarity of the coupling constants and from the shielding of the 3β- and 5-protons in **49** and the 3α-proton in **50** by the methyl groups.[19] In addition, the ^{13}C NMR spectrum of **50** shows the expected shifts relative to **49** for the methyl carbon and C_4, C_5, and C_6 due to the γ-gauche shielding effects.[20] The stereochemistry of **47** and **48** can be assigned similarly. The coupling constants for **47** follow those of **19** precisely. The 3α-methyl group of **48** as expected causes a change in conformation to **67**, leading to very different coupling constants. Again, the α-methyl group of **48** shields $H_{4\alpha}$, and the β-methyl group of **47** shields $H_{4\beta}$.[19]

(15) Kaplan, F.; Schultz, C. O.; Weisleder, D.; Klopfenstein, C. *J. Org. Chem.* **1968**, *33*, 1728. Bates, R. B.; Thalacker, V. P. *J. Org. Chem.* **1968**, *33*, 1730.
(16) Nerdel, F.; Frank, D.; Marschall, H. *Chem. Ber.* **1967**, *100*, 720.
(17) Rey, M.; Roberts, S. M.; Dreiding, A. S.; Roussel, A.; Vanlierde, H.; Toppet, S.; Ghosez, L. *Helv. Chim. Acta* **1982**, *65*, 703.
(18) Fleming, I.; Williams, D. H. *Tetrahedron* **1967**, *23*, 2747.
(19) Anteunis, M.; Danneels, D. *J. Magn. Reson.* **1975**, *7*, 345.
(20) Cf.: Wehrli, F. W.; Wirthlin, T. "Interpretation of Carbon-13 NMR Spectra"; Heyden: London, 1978.

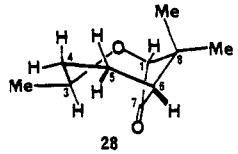
The structure and stereochemistry of the C_5-methyl-substituted adducts **14–18** and **30** are assigned analogously. The proton chemicals shifts and available coupling constants are similar to those of **19** and **47–50**. The methyl groups of **17** and **18** shield $H_{3\beta}$ and $H_{3\alpha}$, respectively, while the methyl groups of **15** and **16** shield $H_{4\beta}$ and $H_{4\alpha}$, respectively.[19] The coupling constants indicate that **14**, **15**, **18**, and **30** adopt the conformation shown in **66**. The 3α-methyl isomer **16**, which possesses similar coupling constants to **48**, also adopts the conformation shown in **67**. Steric interaction between the 4β- and 5-methyl groups of **17** also produces a change in conformation. The ^{13}C NMR spectra indicate that the 4α-methyl of **18** shields C_6, while the 4β-methyl of **17** shields the C_5-methyl group.[20] The ^{13}C NMR spectra also indicate that C_3 of the 3α-methyl isomers **16** and **48** is deshielded relative to C_3 of the 3β-methyl isomers **15** and **47**.

The cyclization of the keteniminium salt prepared from **44** gives cyclobutanones **52–54**. The structures of **52** and **53** are assigned on the basis of the close proximity of the proton and carbon chemical shifts and coupling constants to those for the other oxabicyclo[3.2.0]heptanones. The proton spectrum of **52** is virtually identical (both chemicel shifts and coupling constants) with that of **19** with the exception of shielding of H_5. The spectra of **53** and **19** are also very similar, except that the 6α-ethyl group causes slight changes in conformation. The stereochemistry is assigned on the basis of $J_{5,6\alpha}$ = 5 Hz in **52** and $J_{5,6\beta}$ = 9 Hz in **53**. In addition, the γ-gauche effect shields carbons 4–6 and the ethyl CH_2 in the ^{13}C NMR spectrum of the α-ethyl isomer **53**.[20]

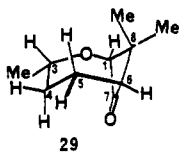
The structure of the oxabicyclo[3.1.1]heptanones follows clearly from the proton chemical shifts and the coupling constants that are consistent only with the expected conformation indicated in Table VII. In particular, $J_{4\beta,5}$ and $J_{3\beta,4\alpha}$ are both close to 0, indicating dihedral angles of 90°. This constrasts to the oxabicyclo[3.2.0]heptanones in which $J_{4\beta,5}$ and $J_{3\alpha,4\beta}$ are close to 0. The four-bond coupling of $J_{1,5}$ of 7 Hz is consistent with literature values in related systems.[15] The stereochemistry of **54** follows from $J_{1,7}$ = 3.5 Hz. If the ethyl group had the opposite stereochemistry, $J_{1,7}$ would be 0 Hz as in **32**.

The cyclization of the ketene prepared from **12** gives two cycloadducts **31** and **32**. The ^1H NMR data for **31** correspond closely to that reported for the other oxabicyclo-[3.2.0]heptanones in Tables IV and V. Similarly, the data for **32** correspond closely to that reported for the other oxabicyclo[3.1.1]heptanones in Table VII. The coupling of $J_{1,7}$ = 0 Hz is consistent with the expected dihedral angle of 90°.

The stereochemistry of the bicyclo[4.1.1]octanones **28** and **29** follows from analysis of the proton shifts and coupling constants that suggests that the conformations are as indicated below. The stereochemistry of **29** is confirmed by the 10% NOE enhancement of H_3 on irradiation of the *endo*-methyl group.

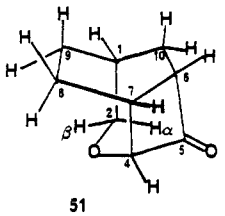


28

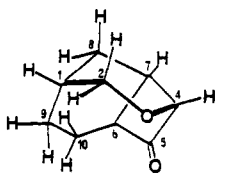


29

The cyclization of the keteniminium salt prepared from **43** could give **51** or the regioisomer **68**. The chemical shifts and couplings are in complete accord with the proposed structure **51**. The assignment is confirmed by the long-range *W* coupling between $H_{2\beta}$ and $H_{10\beta}$ (δ 1.77) of 1.5 Hz. Decoupling establishes that $H_{10\beta}$ is coupled to H_6 (δ 3.5) with J = 6 Hz. These data can be accommodated to **68** only if H_7 absorbs at δ 3.25, rather than the δ 2.55 value assigned to H_7 of **51**.

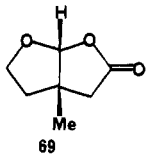


51

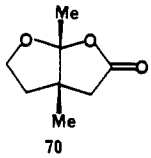


68

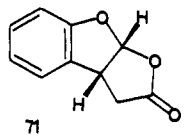
Synthetic Applications. The major goal of this investigation, the use of readily available (alkenyloxy)ketenes and keteniminium salts to demonstrate the scope and limitations of intramolecular ketene and keteniminium salt cycloadditions, has been successfully accomplished. The unexpected ease of formation of the bicyclo[3.1.1]heptanones led us to extend the reaction to the all-carbon system[4] and use it for short syntheses of β-pinene, chrysanthenone, β-*trans*-bergamotene and β-*cis*-bergamotene.[10] The oxabicyclo[3.2.0]heptanones prepared here are useful synthetic intermediates. Baeyer–Villiger oxidation of **14**, **23**, and **30** to give **69–71**, respectively, proceeds in 90–95% yield. The two-step conversion of **11** to **71** proceeds in 66% yield if **30** is not purified. As expected the Baeyer–Villiger oxidation is facile,[21] and the oxygen-bearing substituent migrates.[22] This approach is therefore of interest as a potential route to aflatoxins[23] and neoclerodane insect antifeedants.[24]



69



70



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Experimental Section

NMR spectra were obtained at 90 MHz on Varian EM390, Perkin-Elmer R-32, and Bruker WH 90 spectrometers, at 300 MHz on a Varian XL-300 spectrometer, and at 500 MHz on a homebuilt spectrometer. ^{13}C NMR were recorded on Bruker WH 90 and Varian XL-300 spectrometers. IR spectra were obtained on a Perkin-Elmer 683 spectrometer. Combustion analyses were performed by Galbraith Laboratories. Melting points are uncorrected.

Benzene and dichloroethane were freshly distilled from CaH_2 under N_2 into the reaction flasks immediately prior to use. Collidine and NEt_3 were distilled from CaH_2 and stored under N_2. THF was distilled from sodium benzophenone under N_2. Column chromatography was performed under positive N_2 pressure using silica gel G (type 60, Merck 7731) for flash columns. All reactions were run in oven-dried glassware under N_2. Solvents and reagents were added via dried syringes through septa.

Preparation of Starting Materials. Bromoacetic acid dissolved in ether was passed through acidic alumina. The resulting solution was evaporated under reduced pressure. Bromo-*N*,*N*-dimethylacetamide and bromo-*N*,*N*-diethylacetamide were prepared from bromoacetyl bromide and the corresponding secondary amine by the literature procedure.[25] 2,3-Dimethyl-3-buten-1-ol

(21) (a) Howard, C. C.; Newton, R. F.; Reynolds, D. P.; Wadsworth, A. H.; Kelly, D. R.; Roberts, S. M. *J. Chem. Soc., Perkin Trans. 1* **1980**, 852. (b) Ali, S. M.; Lee, T. V.; Roberts, S. M.; Newton, R. F. *J. Chem. Soc., Perkin Trans. I* **1979**, 708.

(22) Dave, V.; Warnhoff, E. W. *J. Org. Chem.* **1983**, *48*, 2590.

(23) Schuda, P. F. "Topics in Current Chemistry"; Springer-Verlag: Berlin, 1980; Vol. 91, pp 75–111.

(24) (a) Kojima, Y.; Kato, N. *Tetrahedron Lett.* **1979**, 4667. (b) Kojima, Y.; Kato, N. *Agric. Biol. Chem.* **1980**, *44*, 855. (c) Kojima, Y.; Kato, N. *Tetrahedron* **1981**, *37*, 2527. (d) Jalali, M.; Roussai, G.; Lallemand, J.-Y. *Tetrahedron Lett.* **1983**, *24*, 4307 and references cited therein.

and 2-(1-cyclohexenyl)ethanol were prepared by Me_2AlCl-catalyzed ene reactions.[26] *o*-Vinylphenol[27] and 4-methyl-3-penten-1-ol[28] were prepared by literature procedures. 3-Cyclohexene-1-methanol[29] was prepared by reduction of the commercially available aldehyde. All other alkenols were commerical samples.

Preparation of (Alkenyloxy)acetic Acids. The alkenol was dissolved in anhydrous THF under N_2 and treated with NaH (2.2 equiv, 60% dispersion in mineral oil). The mixture was stirred for 20 min and treated with 1 equiv of bromoacetic acid. After the effervescence had subsided, the mixture was heated at reflux for 3–6 h and stirred at room temperature overnight. The reaction mixture was diluted with ether and quenched with saturated brine and enough water to dissolve all the salts. The aqueous layer was adjusted to pH 10.5 with Na_2CO_3 solution. The aqueous layer was separated, washed twice with ether, acidified to pH 1 with concentrated HCl, and extracted with three portions of ether. The combined extracts were washed with water and brine, dried (Na_2SO_4), and evaporated in vacuo to give the pure (alkenyloxy)acetic acid in 70–90% yield.

5-Methyl-2-oxabicyclo[3.2.0]heptan-7-one (14). Acid **1** (0.20 g, 1.39 mmol) was dissolved in 2 mL of dry benzene. Oxalyl chloride (1.4 mL, ~10 equiv) was added, and the solution was heated at reflux for 1.5 h with exclusion of water. The solution was cooled and evaporated in vacuo. The residue was taken up in benzene and evaporated in vacuo. This process was repeated twice to removal all of the excess oxalyl chloride. The resulting acid chloride was taken up in 3 mL of benzene and added via syringe to a solution of NEt_3 (0.27 mL, 1.4 equiv) in 20 mL of benzene at reflux under N_2. The solution was refluxed for an additional 1.5 h, cooled, and poured into 20 mL of saturated NH_4Cl solution. The organic phase was separated, washed with saturated NH_4Cl solution and brine, and dried (Na_2SO_4). Evaporation of the solvent in vacuo at 0 °C gave 145 mg of crude **14**. Chromatography on silica gel (CH_2Cl_2) gave 126 mg (72%) of pure **14** as a colorless volatile liquid: IR (neat) 1783 cm^{-1}. Anal. Calcd for $C_7H_{10}O_2$: C, 66.65; H, 7.99. Found: C, 66.47; H, 8.03.

3,5-Dimethyl-2-oxabicyclo[3.2.0]heptan-7-ones (15, 16). Acid **2** (0.184 g, 1.16 mmol) was converted to the acid chloride and added to NEt_3 in benzene at reflux (2.5 h) as described above. Normal workup gave 265 mg of crude product. Chromatography on silica gel (8:2 hexane–EtOAc) gave 12 mg (7%) of **15** followed by 107 mg (66%) of **16**.

The data for **15** follow: IR (neat) 1783 cm^{-1}. The (2,4-dinitrophenyl)hydrazone (mp 152–156 °C dec; EtOH–H_2O) was prepared as an analytical sample. Anal. Calcd for $C_{14}H_{16}N_4O_5$: C, 52.50; H, 5.04; N, 17.49. Found: C, 52.60; H, 5.00; N, 17.21. In an NOE experiment irradiation of $H_{3\alpha}$ gave a 3% enhancement of $H_{4\alpha}$, 1.4% enhancement of the C_3-Me, and no change for H_1 or H_5-Me.

The data for **16** follow: IR ($CDCl_3$) 1788 cm^{-1}. The (2,4-dinitrophenyl)hydrazone (mp 170–174 °C dec; EtOH–H_2O) was prepared as an analytical sample. Anal. Calcd for $C_{14}H_{16}N_4O_5$: C, 52.50; H, 5.04; N, 17.49. Found: C, 52.20; H, 5.06; N, 17.22.

4,5-Dimethyl-2-oxabicyclo[3.2.0]heptan-7-ones (17, 18). Acid **3** (0.180 g, 1.14 mmol) was converted to the acid chloride and added to NEt_3 in benzene at reflux (2 h) as described above. Normal workup gave 124 mg of crude product. Chromatography on silica gel (8:2 hexane–acetone) gave 98 mg (63%) of an inseparable 1:1.3 mixture of **17** and **18**: IR (neat) 1785 cm^{-1}. Anal. Calcd for $C_8H_{12}O_2$: C, 68.54; H, 8.63. Found: C, 68.37; H, 8.68.

2-Oxabicyclo[3.2.0]heptan-7-one (19). Acid **4** (0.090 g, 0.7 mmol) was converted to the acid chloride and added to NEt_3 in benzene at reflux. The solution was heated at reflux for 24 h and worked up to give crude product containing some anhydride and amide. Chromatography on silica gel (2:1 hexane–EtOAc) gave 12 mg (16%) of **19**: IR (neat) 1785 cm^{-1}. The semicarbazone (mp 228–230 °C dec; H_2O) was prepared as an analytical sample. Anal. Calcd for $C_7H_{11}N_3O_2$: C, 49.70; H, 6.55; N, 24.84. Found: C, 49.63; H, 6.75; N, 24.58.

Paquette et al. have prepared a compound tentatively identified as **19**.[30] Its spectral data (δ 4.05 (d, J = 2.5 Hz)) and physical characteristics (semicarbazone mp 177–179 °C) make it clear that its structure is not **19**.

6-Methyl-2-oxabicyclo[4.2.0]octan-8-one (20). Acid **5** (0.19 g, 1.20 mmol) was converted to the acid chloride (<50 min at reflux) and added to NEt_3 in benzene at reflux (3 h) as described above. Normal workup gave 139 mg of crude product. Chromatography on silica gel (CH_2Cl_2) gave 94 mg (62%) of **20**: NMR ($CDCl_3$) δ 4.41 (dd, 1, J = 2, 2 Hz, H_1), 3.82 (dddd, 1, J = 1.7, 2.5, 4, 11.5 Hz, H_3), 3.55 (ddd, 1, J = 2, 2, 11.5 Hz, H_3), 2.56 (dd, 1, J = 2, 16 Hz, H_7), 2.42 (dd, 1, J = 2, 16 Hz, H_7), 2.02 (br d, 1, J = 14 Hz, H_5), 1.41–1.71 (m, 3, H_5, H_4, H_4), 1.50 (s, 3); ^{13}C NMR ($CDCl_3$) δ 205.2 (C_8), 87.9 (C_1), 64.5 (C_3), 52.8 (C_7), 33.0 (C_5), 28.1 (C_6), 24.6 (Me), 20.8 (C_4); IR (neat) 1789 cm^{-1}. Cyclobutanone **20** decomposes slowly at −20 °C. The semicarbazone (mp 211–212 °C; EtOH–H_2O) was prepared as an analytical sample. Anal. Calcd for $C_9H_{15}N_3O_2$: C, 54.81; H, 7.67; N, 21.30. Found: C, 54.64, H, 7.81; N, 21.34.

3,6-Dimethyl-2-oxabicyclo[4.2.0]octan-8-ones (21, 22). Acid **6** (0.18 g, 1.05 mmol) was converted to the acid chloride, which was a 1:1 mixture of the desired acid chloride and that in which HCl added to the double bond, and added to NEt_3 in benzene at reflux (2.5 h) as described above. Normal workup followed by chromatography on silica gel (4:1 hexane–EtOAc) gave 45 mg (58% based on acid chloride) of **21** and **22** as an inseparable 3:2 mixture of isomers: NMR ($CDCl_3$) δ (major) 4.42 (dd, 1, J = 1.5, 1.7 Hz), 3.55 (m, 1), 2.50 (dd, 1, J = 1.5, 15.9 Hz), 2.30 (dd, 1, J = 1.7, 15.9 Hz), 1.48 (s, 3), 1.14 (d, 3, J = 6.2 Hz), 2.1–1.3 (m, 4), (minor) δ 4.18 (dd, 1, J = 2.2, 3.2 Hz), 3.55 (m, 1), 2.84 (dd, 1, J = 2.2, 16.8 Hz), 2.56 (dd, 1, J = 3.2, 16.8 Hz), 1.33 (s, 3), 1.19 (d, 3, J = 6.3 Hz), 2.1–1.3 (m, 4); ^{13}C NMR ($CDCl_3$) δ (major) 205.9, 89.2, 70.6, 52.6, (minor) δ 206.3, 89.3, 70.0, 52.9, (unassigned) δ 33.7, 30.0, 29.3, 28.3, 27.6, 27.4, 26.2, 24.6, 21.8, 21.5; IR ($CDCl_3$) 1785 cm^{-1}. The semicarbazone (mp 227–229 °C dec; EtOH–H_2O) was prepared as an analytical sample. Anal. Calcd for $C_{10}H_{17}N_3O_2$: C, 56.85; H, 8.11; N, 19.89. Found: C, 57.28; H, 8.21; N, 19.76.

***cis*-2a,7b-Dihydrocyclobuta[*b*]benzofuran-2(1*H*)-one (23).** Acid **7** (0.18 g, 1.01 mmol) was converted to the acid chloride and added to NEt_3 in benzene at reflux (2 h) as described above. Normal workup, followed by chromatography on silica gel (CH_2Cl_2), gave 112 mg (70%) of pure **23**: mp 31–32 °C; NMR ($CDCl_3$) δ 7.22 (dddd, 1, J = 7, 1.5, 0.7, 0.7 Hz), 7.15 (dddd, 1, J = 7.5, 7.5, 1.5, 0.6 Hz), 6.88 (ddd, 1, J = 7, 7.5, 1.3 Hz), 6.82 (dddd, 1, J = 7.5, 1.3, 0.7, 0.7 Hz), 5.65 (ddd, 1, J = 3, 3, 7.5 Hz), 4.14 (br ddd, 1, J = 3.8, 7.5, 8.4 Hz), 3.58 (ddd, 1, J = 3, 8.4, 17.7 Hz) 2.80 (ddd, 1, J = 3, 3.8, 17.7 Hz); ^{13}C NMR ($CDCl_3$) δ 205.4 (C_2), 160.7 (C_{3a}), 128.9 (C_5), 127.8 (C_{7a}), 125.6 (C_6), 122.0 (C_7), 110.5 (C_4), 94.3 (C_{2a}), 55.7 (C_1), 35.0 (C_{7b}); IR (melt) 1791, 1611, 1593, 1476, 1461, 750 cm^{-1}. Anal. Calcd for $C_{10}H_8O_2$: C, 74.99; H, 5.03. Found: C, 75.06; H, 5.15.

Preparation and Reactions of the Ketene Derived from 8. Acid **8** (0.18 g, 1.28 mmol) was converted to the acid chloride and added to NEt_3 in benzene at reflux as described above. The solution was heated at reflux for 4 h and worked up to give 180 mg of crude product, which contained no cyclobutanone by IR. Preparative TLC (silica gel, 9:1 hexane–EtOAc) gave, in order of increasing polarity, the unstable furan **24** (25 mg, 16%), the unstable furan **25** (15 mg, 10%), and the furanone **26** (35 mg, 22%).

The data for **24** follow: NMR ($CDCl_3$) δ 6.79 (d, 1, J = 1.8 Hz), 5.77 (qq, 1, J = 1.4, 1.4 Hz), 4.83 (m, 2), 4.45 (dd, 1, J = 9.3, 10.7 Hz), 4.12 (dd, 1, J = 6, 9.3 Hz), 3.93 (t, 2, J = 6.3 Hz), 3.85 (ddd, 1, J = 1.8, 6, 10.7 Hz), 2.70 (t, 2, J = 6.3 Hz), 1.74 (t, 3, J = 1 Hz), 1.57 (br s, 3), 1.54 (br s, 3); IR (neat) 3145, 3105, 3082, 1760, 1693, 1650, 1240, 1190, 1155, 1110, 1055, 940, 840, cm^{-1}; UV (MeOH; λ_{max} nm (ϵ)] 253 (3800).

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The data for **25** follow: NMR ($CDCl_3$) δ 6.78 (d, 1, J = 2 Hz), 5.35 (br t, 1, J = 7.5 Hz), 4.81 (m, 2), 4.46 (dd, 1, J = 9, 10.7 Hz), 4.2–4.0 (m, 3), 4.10 (s, 2) 3.85 (ddd, 1, J = 2, 6, 10.7 Hz), 1.72 (br s, 6), 1.66 (br, 3); IR (neat) 3150, 3103, 3082, 1772, 1755, 1675, 1650, 1240, 1200, 1110, 940, 910, 845 cm^{-1}.

The data for **26** follow: NMR ($CDCl_3$) δ 4.73 (m, 2), 4.02 (s, 2), 2.20 (t, 3, J = 2 Hz), 1.75 (br s, 3); IR (neat) 1722, 1645 cm^{-1}.

7,7-Dimethyl-2-oxabicyclo[3.1.1]heptan-6-one (27). Acid **9** (0.18 g, 1.14 mmol) was converted to the acid chloride and added to NEt_3 in benzene at reflux (3.5 h) as described above. Normal workup gave 127 mg of crude product. Chromatography on silica gel (4:1 hexane–EtOAc) gave 85 mg (52%) of **27** as a colorless liquid with a camphoraceous odor: ^{13}C NMR ($CDCl_3$) δ 207.4 (C_6), 93.6 (C_1), 63.7 (C_3), 61.9 (C_5), 33.2 (C_7), 29.1 (C_4), 24.0 (*exo*-Me), 14.9 (*endo*-Me); IR (neat) 1785, 1393, 1373, 1092, 1072, 910 cm^{-1}. Anal. Calcd for $C_8H_{12}O_2$: C, 68.54; H, 8.63. Found: C, 68.45; H, 8.42.

3,8,8-Trimethyl-2-oxabicyclo[4.1.1]octan-7-ones (28, 29). Acid **10** (0.18 g, 0.96 mmol) was converted to the acid chloride and added to NEt_3 in benzene at reflux. The solution was heated for 39 h at reflux and worked up to give 185 mg of crude product. Chromatography on silica gel (9:1 hexane–EtOAc) gave 24 mg (13%) of **28** followed by 30 mg (17%) of **29**.

The data for **28** follow: NMR ($CDCl_3$) δ 4.25 (d, 1, J = 7 Hz, H_1) 3.78 (ddq, 1, J = 1.2, 11.5, 6 Hz, $H_{3\alpha}$), 2.79 (ddd, 1, J = 3, 5, 7 Hz, H_6), 2.01–1.83 (m, 3), 1.74 (dddd, 1, J = 1.2, 1.2, 7, 14 Hz, $H_{4\alpha}$), 1.36 (s, 3, endo), 1.26 (d, 3, J = 6 Hz), 1.10 (s, 3, exo); ^{13}C NMR ($CDCl_3$) δ 210.0 (C_7), 97.4 (C_1), 74.9 (C_3), 68.1 (C_6), 35.6 (C_8), 34.7 (C_4), 27.7 (*exo*-Me), 23.8 (C_5), 22.9 (Me), 16.8 (*endo*-Me); IR (neat) 1780 cm^{-1}.

The data for **29** follow: NMR ($CDCl_3$) 4.37 (ddq, 1, J = 1, 1.2, 12, 6 Hz, $H_{3\beta}$), 4.08 (d, 1, J = 6.7 Hz, H_1), 2.98 (br dd, 1, J = 7, 7 Hz, H_6), 1.88 (dddd, 1, J = 4, 4, 7.5, 14 Hz, $H_{5\alpha}$) 1.84 (br ddd, 1, J = 4, 4, 14.5 Hz, $H_{4\beta}$), 1.75 (br ddd, 1, J = 4, 14, 14.5 Hz, $H_{5\beta}$), 1.52 (dddd, 1, J = 4, 12, 14, 14.5 Hz, $H_{4\alpha}$), 1.38 (s, 3, endo), 1.20 (d, 3, J = 6 Hz), 1.14 (s, 3, exo); ^{13}C NMR ($CDCl_3$) δ 209.7 (C_7), 95.9 (C_1), 73.4 (C_3), 68.1 (C_6), 35.7 (C_8) 35.2 (C_4), 29.4 (*exo*-Me), 23.5 (Me), 20.7 (C_5), 17.5 (*endo*-Me); IR (neat) 1784 cm^{-1}.

1,5-Dimethyl-2-oxabicyclo[3.2.0]heptan-7-one (30). Acid **11** (0.25 g, 1.58 mmol) was converted to the acid chloride and added to NEt_3 in benzene at reflux as described above. Normal workup after 3.3 h at reflux gave 199 mg of crude product. Chromatography on silica gel (4:1 hexane–EtOAc) gave 111 mg (50%) of **30** as a colorless liquid: IR (neat) 1779 cm^{-1}. Anal. Calcd for $C_8H_{12}O_2$: C, 68.54; H, 8.63. Found: C, 68.29; H, 8.49.

9-Oxatricyclo[6.3.0.0^{1,6}]undecan-7-one (31) and 8-Oxatricyclo[5.3.1.0^{1,6}]undecan-11-one (32). Acid **12** (0.18 g, 1.06 mmol) was converted to the acid chloride and added to NEt_3 in benzene at reflux (4 h) as described above. Normal workup gave 134 mg of crude product. Chromatography on silica gel (4:1 hexane–EtOAc) gave 8 mg (5%) of **32** as a pale yellow oil followed by 94 mg (58%) of **31** as an oil that solidified on standing.

The data for **31** follow: mp 50–53 °C (MeOH–H_2O); ^{13}C ($CDCl_3$) δ 211.6 (C_7), 94.5 (C_8, J = 160 Hz), 69.2 (C_{10}, J = 147 Hz), 57.5 (C_6, J = 135 Hz), 41.9 (C_1), 40.0 (C_{11}, J = 132 Hz), 29.4 (C_2, J = 127 Hz), 22.3 ($C_{3,4or5}$, J = 126 Hz), 22.2 ($C_{3,4or5}$, J = 126 Hz), 21.3 ($C_{3,4or5}$, J = 127 Hz); IR (neat) 1779 cm^{-1}. Anal. Calcd for $C_{10}H_{14}O_2$: C, 72.26; H, 8.49. Found: C, 71.99; H, 8.49.

The data for **32** follow: NMR ($CDCl_3$) δ 4.34 (s, 1, H_7), 4.04 (ddd, 1, J = 1.8, 7, 11.2 Hz, $H_{9\alpha}$), 3.86 (ddd, 1, J = 5.6, 11.2, 11.2 Hz, $H_{9\beta}$), 2.40 (ddd, 1, J = 7.1, 11.2, 12.4 Hz, $H_{10\alpha}$), 2.03 (ddd, 1, J = 1.8, 5.6, 12.4 Hz, $H_{10\beta}$), 1.99 (dd, 1, J = 7.2, 13.7 Hz, H_6), 1.94 (br d, 1, J = 14 Hz, $H_{2\beta}$), 1.64–1.51 (m, 3), 1.27 (ddddd, 1, J = 3.8, 3.8, 13.1, 14.4, 14.4 Hz, $H_{3\beta}$), 1.17 (ddd, 1, J = 4.4, 13.8, 13.8 Hz, $H_{2\alpha}$), 1.09 (ddddd, 1, J = 2.5, 2.5, 13.1, 13.1, 13.7 Hz, $H_{4\alpha}$), 0.77 (dddd, 1, J = 3.5, 13.7, 13.7, 16.8 Hz, $H_{5\beta}$); ^{13}C NMR ($CDCl_3$) δ 93.6 (C_7), 66.0 (C_1), 63.5 (C_9), 41.7 (C_6), 39.9 (C_{10}), 26.4 (C_2), 23.9, 22.9 and 21.8 ($C_{3,4and5}$); IR (neat) 1779 cm^{-1}.

[(3-Methyl-3-butenyl)oxy]-*N*,*N*-dimethylacetamide (35). 3-Methyl-3-buten-1-ol (2.26 g, 26.3 mmol) was dissolved in 60 mL of dry THF. NaH (1.05 g of 60% dispersion, unwashed, 26.3 mmol) was added and the solution stirred for 20 min under N_2. Bromo-*N*,*N*-dimethylacetamide (4.37 g, 26.3 mmol) was added, and the reaction mixture was heated at reflux for 6 h and stirred at room temperature overnight. The mixture was diluted with 90 mL of ether and quenched with saturated brine, followed by just enough water to dissolve all the salts. The organic layer was separated, and the aqueous layer was extracted twice with 40 mL of ether. The combined organic layers were washed with saturated brine, dried ($MgSO_4$), and evaporated in vacuo to give 3.96 g of crude product (~79% adjusting for mineral oil). Distillation (108–111 °C, 4 torr) gave 2.83 g (63%) of **35** as a colorless liquid: NMR ($CDCl_3$) δ 4.70 (m, 2), 4.07 (s, 2), 3.57 (t, 2, J = 7 Hz), 2.95 (s, 3), 2.89 (s, 3), 2.26 (br t, 2, J = 7 Hz), 1.67 (s, 3).

5-Methyl-2-oxabicyclo[3.2.0]heptan-7-one (14). The keteniminium salt was prepared and reacted by a modification of the procedure of Ghosez et al.[11] Amide **35** (0.2 g, 1.07 mmol) was dissolved in 40 mL of dry benzene under N_2. Collidine (0.16 mL, 1.05 equiv) was added, and the solution was heated at reflux. A solution of Tf_2O (0.22 mL, 1.1 equiv) in 15 mL of dry benzene was added over 30 min via an addition funnel. The reaction mixture acquired a yellow-orange color that intensified as the addition of Tf_2O progressed. An orange oil gradually formed and separated. The solution was heated at reflux for 2 h, cooled to 25 °C, and evaporated in vacuo. The residual oil was washed with ether and then taken up in 10 mL of CH_2Cl_2 and 10 mL of water. The two-phase mixture was stirred for 24 h at 25 °C, and the CH_2Cl_2 was removed in vacuo at 10 °C to leave a yellow aqueous layer containing brownish gum. This was extracted three times with CCl_4. The combined CCl_4 layers were washed with water and brine, dried (Na_2SO_4), and evaporated in vacuo (<10 °C) to give 92 mg of **14** which was >95% pure. The combined aqueous layers were extracted twice with CH_2Cl_2. The combined CH_2Cl_2 layers were washed with water and brine, dried (Na_2SO_4), and evaporated in vacuo to give 80 mg of **14** (~40 mg) and collidinium triflate. The two fractions were combined and chromatographed on silica gel (4:1 hexane–EtOAc) to give 120 mg (81%) of pure **14**, which was spectroscopically identical with that prepared from the ketene.

3,5-Dimethyl-2-oxabicyclo[3.2.0]heptan-7-ones (15, 16). Amide **36** (0.20 g) was converted to the keteniminium salt and cyclized as described above. The CCl_4 layer gave 123 mg (82% ~92% pure, 74% corrected) of an 88:12 mixture of **15** and **16**, respectively.

4,5-Dimethyl-2-oxabicyclo[3.2.0]heptan-7-ones (17, 18). Amide **37a** (0.20 g) was converted to the keteniminium salt and cyclized as described above (2.2-h reflux). The CCl_4 layer gave 116 mg (77%, ~92% pure, 69% corrected) of a 1:4 mixture of **17** and **18**. The CH_2Cl_2 layer gave a mixture containing ~12 mg (8%) of **17** and **18**.

Amide **37b** (0.15 g) was converted to the keteniminium salt and cyclized as described above (2.5-h reflux). The CCl_4 layer gave 92 mg (92%, ~92% pure, 83% corrected) of a 1:7 mixture of **17** and **18**.

2-Oxabicyclo[3.2.0]heptan-7-one (19). Amide **38** (0.20 g) was converted to the keteniminium salt and cyclized as described above except that the reaction was heated at reflux for 16 h. The CCl_4 layer gave 35 mg of pure **19**. The CH_2Cl_2 layer contained ~78 mg of **19** by NMR analysis. The total yield of **19** was 113 mg (79%).

3-Methyl-2-oxabicyclo[3.2.0]heptan-7-ones (47, 48). Amide **41** (0.30 g) was converted to the keteniminium salt and cyclized as described above except that the reaction was heated at reflux for 17 h. Workup and hydrolysis gave a light brown CH_2Cl_2 layer and an aqueous layer. The CH_2Cl_2 layer was washed with brine, dried, filtered through silica gel, and treated with activated charcoal. The resulting CH_2Cl_2 solution was washed with 5% HCl solution and brine, dried (Na_2SO_4), and evaporated in vacuo to give 120 mg (~92% pure, 58%) of 10:1 mixture of **47** and **48** as a volatile yellow liquid. Chromatography on silica gel (4:1 hexane–EtOAc) gave 70 mg (36%) of **47** followed closely by 7 mg (4%) of **48**.

The data for **47** follow: IR (neat) 1784 cm^{-1}. The semicarbazone (mp 209–211 °C; EtOH–H_2O) was prepared as an analytical sample. Anal. Calcd for $C_8H_{13}N_3O_2$: C, 52.45; H, 7.15; N, 22.94. Found: C, 52.23; H, 6.91; N, 22.70.

The data for **48** follow: IR (neat) 1788 cm^{-1}.

4-Methyl-2-oxabicyclo[3.2.0]heptan-7-ones (49, 50). Amide **42** (0.20 g) was converted to the keteniminium salt and cyclized as described above, except that the reaction was heated for 17 h at reflux. Normal workup as described above for the preparation of **14** gave 93 mg (>95% pure, 60%) of a 45:55 mixture of **49** and

50 from the CCl_4 layer as a volatile liquid. Chromatography on silica gel (9:1 hexane–EtOAc) gave 25 mg (19%) of **49** followed closely by 32 mg (22%) of **50**.

The data for **49** follow: IR (neat) 1785 cm^{-1}.

The data for **50** follow: IR (neat) 1785 cm^{-1}. The semicarbazone (mp 215–218 °C dec; EtOH–H_2O) was prepared as an analytical sample. Anal. Calcd for $C_8H_{13}N_3O_2$: C, 52.45; H, 7.15; N, 22.94. Found: C, 52.23; H, 6.98; N, 22.62.

6-Methyl-2-oxabicyclo[4.2.0]octan-8-one (20). Amide **39** (0.20 g) was converted to the keteniminium salt and cyclized as described above (2.3-h reflux) for the preparation of **14**. Workup and hydrolysis gave 137 mg of a complex mixture. Chromatography on silica gel (4:1 hexane–EtOAc) gave 50 mg (33%) of pure **20**, which was identical with that prepared from the ketene.

3,6-Dimethyl-2-oxabicyclo[4.2.0]octan-8-ones (21, 22). Amide **40** (0.20 g) was converted to the keteniminium salt and cyclized as described above (3-h reflux). The oil obtained from the CCl_4 layer was chromatographed on silica gel (9:1 hexane–EtOAc) to give 29 mg (19%) of an inseparable 7:3 mixture of *E*- and *Z*-**46** followed by 25 mg (16%) of **21** and **22** as a mixture of isomers.

The data for *E*- and *Z*-**46** follow: NMR ($CDCl_3$) (*E*-**46**) δ 5.55 (dq, 1, J = 15.5, 6.4 Hz), 5.44 (dt, 1, J = 15.5, 8.2 Hz), 4.03 (s, 2), 2.45 (d, 1, J = 18.1 Hz), 2.31 (br d, 2, J =8.2 Hz), 2.24 (d, 1, J = 18.1 Hz), 1.69 (br d, 3, J = 6.4 Hz), 1.34 (s, 3), (*Z*-**46**) δ 5.68 (dtq, 1, J = 11.2, 1, 7.3 Hz), 5.45 (m, 1), 4.05 (s, 2), 2.44 (d, 1, J = 18.2 Hz), 2.40 (br d, 2, J = 9 Hz), 2.28 (d, 1, J = 18.2 Hz), 1.64 (td, 3, J = 1, 7.3 Hz), 1.36 (s, 3); ^{13}C NMR ($CDCl_3$) (*E*-**46**) δ 215.9, 129.7, 125.4, 70.2, 47.4, 43.5, 25.2, 18.0, one carbon not seen, (*Z*-**46**) δ 215.9, 127.6, 124.5, 70.2, 47.5, 37.4, 25.2, 12.9, one carbon not seen; IR (neat) 3025, 1762 cm^{-1}.

52–54. Amide **44** (0.10 g) was converted to the keteniminium salt and cyclized as described above, except that the reaction was heated for 18.5 h at reflux. Normal workup as described above gave a light yellow oil from the CCl_4 extract. Chromatography on silica gel (85:15 hexane-EtOAc) gave 7 mg (9%) of **54** followed by 25 mg (33%) of **52** and 5 mg (7%) of **53**, all as colorless oils.

The data for **52** follow: IR (neat) 1783 cm^{-1}.

The data for **53** follow: IR (neat) 1776 cm^{-1}. The (2,4-dinitrophenyl)hydrazone (mp 127–132 °C dec; EtOH–H_2O) was prepared as an analytical sample. Anal. Calcd for $C_{14}H_{16}N_4O_5$: C, 52.50; H, 5.04; N, 17.49. Found: C, 52.22; H, 4.69; N, 17.33.

The data for **54** follow: ^{13}C NMR ($CDCl_3$) δ 205.0 (C_6), 90.4 (C_1), 63.5 (C_3), 58.6 (C_5), 37.4 (C_7), 27.4 (C_4), 15.7, 12.3; IR ($CDCl_3$) 1779 cm^{-1}.

(*E*)-4-Propylidenetetrahydropyran-3-one (55). Conversion of amide **45** (0.10 g) to the keteniminium salt and cyclization as described above for the cis isomer **44** gave 56 mg of crude **55**. Preparative TLC (4:1 hexane–EtOAc) gave 49 mg (64%) of pure **55**: NMR ($CDCl_3$) δ 6.85 (tt, 1, J = 2.4, 7.5 Hz), 4.18 (s, 2), 3.88 (t, 2, J = 5.7 Hz), 2.65 (dtt, 2, J = 2.4, 1.2, 5.7 Hz), 2.15 (dtq, 2, J = 7.5, 1.2, 7.5 Hz), 1.10 (t, 3, J = 7.5 Hz); IR (neat) 1697, 1615 cm^{-1}.

3-Oxatricyclo[4.3.1.0^{4,7}]decan-5-one (51). Amide **43** (0.20 g) was converted to the keteniminium salt and cyclized as described above (17-h reflux) to give 47 mg of crude product from the CCl_4 layer. Column chromatography on silica gel (2:1 hexane–EtOAc) gave 37 mg (24%) of pure **51** as an oil that solidified to an amorphous solid, mp 40–75 °C, on standing. All attempts at recrystallization failed: NMR ($CDCl_3$) δ 4.73 (dd, 1, $J_{4,7}$ = 6.5, $J_{4,6}$ = 7.0 Hz, H_4), 3.97 (ddd, 1, $J_{2\beta,10\beta}$ = 1.5, $J_{1,2\beta}$ = 5.3, $J_{2\alpha,2\beta}$ = 12 Hz, $H_{2\beta}$), 3.65 (dd, 1, $J_{1,2\alpha}$, $J_{2\alpha,9\beta}$ = 0, 1 or 1, 0, $J_{2\alpha,2\beta}$ = 12 Hz, $H_{2\alpha}$), 3.25 (ddddd, 1, $J_{1,6}$ = 0.7, $J_{4,6} \approx J_{6,7} \approx J_{6,10\alpha} \approx J_{6,10\beta} \approx$ 7 Hz, H_6), 2.55 (dddd, 1, $J_{7,8\alpha}$ = 2.5, $J_{7,8\beta}$ = 4.8, $J_{4,7}$ = 6.5, $J_{6,7}$ = 7 Hz, H_7), 2.2–1.67 (m, 7); decoupling established that $H_{10\beta}$ absorbs at δ 1.77 and is coupled to $H_{2\beta}$ (J = 1.5 Hz) and to H_6 (J = 7 Hz); ^{13}C NMR ($CDCl_3$) δ 211.5 (C_5), 93.2 (C_4, J = 159 Hz), 74.2 (C_2, J = 143 Hz), 57.9 (C_6, J = 148 Hz), 32.9 (C_1, J = 128 Hz), 32.2 (C_7, J = 136 Hz), 26.0 (C_{10}, J = 132 Hz), 22.7 (C_9, J = 128 Hz), 18.2 (C_8, J = 129 Hz); IR ($CDCl_3$) 1775 cm^{-1}.

65c and 65d. Amide **65a** (1.24 g) was converted to the keteniminium salt and cyclized as described above, except that the reaction was heated for 22 h at reflux. Normal workup as described above gave 0.182 g of a yellow oil from the CCl_4 extract. Chromatography on silica gel (95:5 hexane–EtOAc) gave 55 mg (6%) of **65c** followed by 89 mg (6%) of **65d**.

The data for **65c** follow: NMR ($CDCl_3$) δ 5.99 (m, 1), 5.83 (m, 1), 5.64 (m, 1), 4.09 (dd, 1, J = 17.3, 1.3 Hz), 3.76 (d, 1, J = 17.3 Hz), 2.92 (m, 1), 2.66 (m, 2); ^{13}C NMR ($CDCl_3$) δ 208.8, 135.1, 131.0, 88.3, 68.9, 46.8, 35.7.

The data for **65d** follow: NMR ($CDCl_3$) δ 7.4–7.1 (m, 5), 4.72 (br s, 1), 4.25 (d, 1, J = 17.7 Hz), 4.13 (d, 1, J = 17.7 Hz), 3.41 (dd, 1 J = 5.7, 9.0 Hz), 2.99 (br s), 2.6–2.5 (m, 1), 2.2–2.1 (m, 2); ^{13}C NMR ($CDCl_3$) δ 208.6, 143.8, 128.7 (2), 126.6 (2), 126.5, 75.8, 68.5, 56.6, 45.0, 38.8, 34.2; IR ($CDCl_3$) 1725 cm^{-1}.

Tetrahydro-3α-methylfluoro[2,3-*b*]furan-2(3*H*)-one (69). The bicyclic ketone **14** (34 mg) was dissolved in 5 mL of dry CH_2Cl_2. Solid $NaHCO_3$ (67 mg, 3 equiv) of *m*-chloroperbenzoic acid (57 mg, 85% pure, 1.05 equiv) were added to the rapidly stirred solution. The reaction mixture was stirred for 2 h, diluted with 20 mL of CH_2Cl_2, and quenched with 10% aqueous Na_2CO_3 solution. The organic layer was washed with 10% Na_2CO_3 solution and brine, dried (Na_2SO_4), and evaporated in vacuo to give 35 mg (92%) of pure **69**: NMR ($CDCl_3$) δ 5.61 (s, 1), 4.15 (ddd, 1, J = 4.9, 9.3, 16.1 Hz), 4.05 (ddd, 1, J = 6.8, 8.8, 16.1 Hz), 2.70 (d, 1, J = 18.6 Hz), 2.57 (d, 1, J = 18.6 Hz), 2.02–1.89 (m, 2), 1.39 (s, 3); ^{13}C NMR ($CDCl_3$) δ 174.7 (C_2), 113.1 (C_{6a}), 68.5 (C_5), 46.7 (C_{3a}), 42.0 (C_3), 39.3 (C_4), 23.9 (Me); IR (neat) 1782, 1750 (sh) cm^{-1}.

Tetrahydro-3a,6a-dimethylfuro[2,3-*b*]furan-2(3*H*)-one (70). Baeyer–Villiger oxidation of bicyclic ketone **30** (60 mg) as described above gave 60 mg (90%) of pure **71** as a pale yellow oil that crystallized on standing: mp 36–39 °C; NMR ($CDCl_3$) δ 4.04 (ddd, 1, J = 4.7, 8, 9.2 Hz), 3.96 (ddd, 1, J = 8, 8.5, 8.5 Hz), 2.73 (d, 1, J = 18 Hz), 2.56 (d, 1, J = 18 Hz), 2.07 -1.96 (m, 2), 1.51 (s, 3), 1.28 (s, 3); ^{13}C NMR ($CDCl_3$) δ 173.2 (C_2), 118.4 (C_{6a}), 65.7 (C_5, J = 149 Hz), 47.3 (C_{3a}), 42.7 (C_3, J = 132 Hz), 39.3 (C_4, J = 132 Hz), 21.9 (Me, J = 127 Hz), 19.9 (Me, J = 128 Hz); IR (melt) 1770 cm^{-1}. Anal. Calcd for $C_8H_{12}O_3$: C, 61.52; H, 7.74. Found: C, 61.62; H, 7.78.

***cis*-3a,8a-Dihydrofuro[2,3-*b*]benzofuran-2(3*H*)-one (71).** Baeyer–Villiger oxidation of bicyclic ketone **23** (22 mg) as described above give 23 mg (92%) of pure **71** as a colorless oil that crystallized on standing: mp 124–126 °C; lit.[31] mp 124–126 °C; NMR ($CDCl_3$) δ 7.27 (ddd, 1, J = 1.2, 1.2, 7 Hz), 7.23 (br dd, 1, J = 7.8, 7.8 Hz), 7.03 (ddd, 1, J = 1.0, 7.3, 7.3 Hz), 6.94 (br d, 1, J = 7.8 Hz), 6.54 (d, 1, J = 5.9 Hz), 4.23 (br dd, 1, J = 5.9, 9.8 Hz), 3.11 (dd, 1, J = 9.8, 18.1 Hz), 2.80 (dd, 1, J = 2, 18.1 Hz); ^{13}C NMR ($CDCl_3$) δ 173.7 (C_2), 157.2 (C_{7a}), 129.9 (C_6, J = 161 Hz), 126.6 (C_{3b}), 124.7 (C_5, J = 161 Hz), 122.9 (C_4, J = 164 Hz), 110.9 (C_7, J = 163 Hz), 107.6 (C_{8a}, J = 188 Hz) 42.3 (C_{3a}, J = 143 Hz), 34.6 (C_3, J = 133, 140 Hz); IR (neat) 1796, 1791, 1621, 1603, 1480, 1465, cm^{-1}. Anal. Calcd for $C_{10}H_8O_3$: C, 68.18; H, 4.58. Found: C, 68.26; H, 4.73.

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Supplementary Material Available: Experimental and spectral data for (alkenyloxy)acetic acids and (alkenyloxy)acetamides (5 pages). Ordering information is given on any current masthead page.