A Ru Catalyzed Addition of Alkenes to Alkynes

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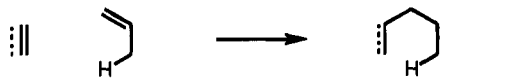
Abstract: The potential of the Alder ene reaction which possesses high atom economy is not realized because of limitations of scope and selectivity. Thus, the thermal bimolecular addition of unactivated alkenes to unactivated alkynes has not been reported. This addition now becomes possible through the advent of ruthenium catalysis. Several ruthenium complexes are effective including $(PhOCH_3)(Ph_3P)RuCl_2$, (*p*-cymene)$(Ph_3P)RuCl_2$, (*p*-cymene)-$[(C_4H_9)_3P]RuCl_2$, and CpRu(COD)Cl, but the latter gives the highest conversions and regioselectivities. The reaction best proceeds in aqueous DMF at 100 °C or methanol at reflux. Both internal and terminal alkynes react. Monosubstituted alkenes are required. The reaction exhibits extraordinary chemoselectivity and control of product double bond geometry. A mechanism envisioning formation of a ruthenacyclopentene accounts for the experimental observations.

Formation of carbon–carbon bonds in a synthetically efficient manner forms the backbone of organic chemistry. In addition to selectivity as a requirement for efficiency, increasing emphasis is placed upon atom economy in order to utilize raw materials more effectively and to minimize waste production.[1] Reactions of the general form A + B → C + D theoretically generate a waste product (if C is the desired product, D is an obligatory waste product). D should be made as small and innocuous as possible with the ideal being the vanishment of D which reduces the reaction to a simple addition, A + B → C. Among reactions that meet this requirement is the Alder ene reaction (eq 1), a process that has found minimal use presumably because of the extreme conditions frequently required, of the lack of selectivity, and of its limitations in terms of reaction partners.[2]



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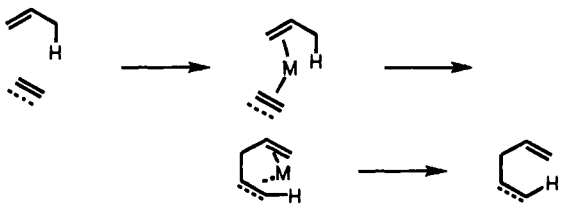
Catalysis of the Alder ene reaction becomes an important objective to expand the applicability of this process. In its simplest form, catalysis involves lowering the energy of the transition state for the one-step process. With enophiles that possess conjugated Lewis basic sites (like α,β-unsaturated carbonyl compounds), Lewis acid catalysis has proven useful.[3] However, the absence of such structural features precludes such an approach. An alternative catalytic concept involves precoordination of the two reactant partners (eq 2) which may undergo



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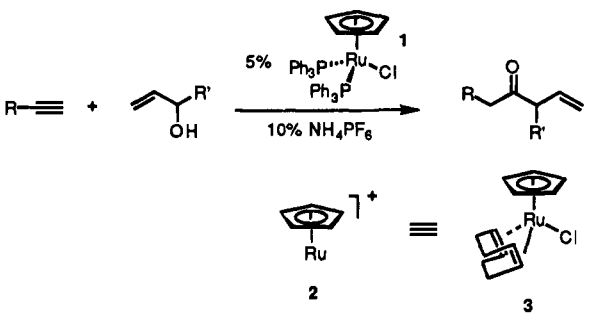
one or more steps to form the desired product. While such an approach is freed of the requirement of a Lewis basic site, it does require some coordination differences to permit bimolecular processes between two different reaction partners. The excellent coordination properties of acetylenes as ligands for transition metals led us to include that group as one partner. The potential problem of this choice lies in their propensity to form metallacyclopentadienes[4] and/or cyclotrimerize to benzenoid aromatics.[5]

In our development[6] of a reconstitutive addition of allyl alcohols and terminal acetylenes (eq 3) via vinylideneruthenium complexes[7] as reactive intermediates, we desired a substitute for **1** that would function as the equivalent of a triply



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coordinatively unsaturated ruthenium species **2** to allow an evaluation of the effect of ligands on this reaction. The common ability to easily displace COD from the coordination sphere of a metal led to the ruthenium complex **3**.[8,9] Using **3** itself in the absence of any additional ligands with the above substrates led to a totally different course, the formation of γ,δ-unsaturated

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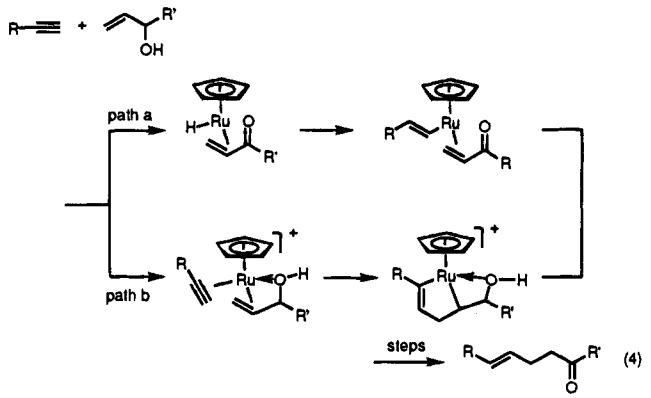
Table 1. Variation of Ruthenium Complex as Catalyst

entry	complex	condition[a] promoter, solvent, temp, time	yield (%)	ratio[b] 4:5
1	**3**	- - -, 1:1 DMF−H_2O, 100 °C, 2 h	56	5.2:1
2	[(*p*-cymene)$RuCl_2$]$_2$	NH_4PF_6, CH_3OH, 65 °C,12 h	11	1.7:1
3	[($PhOCH_3$)$RuCl_2$]$_2$	NH_4PF_6, CH_3OH, 65 °C, 12 h	25	2:1
4	(PhH)(Ph_3P)$RuCl_2$	NH_4PF_6, CH_3OH, 65 °C, 6 h	43	1.8:1
5	($PhOCH_3$)(Ph_3P)$RuCl_2$	NH_4PF_6, CH_3OH, 65 °C, 6 h	47	1.6:1
6	(*p*-cymene)(Ph_3P)$RuCl_2$	NH_4PF_6, CH_3OH, 65 °C, 6 h	50	1.6:1
7	(*p*-cymene)(*n*-$C_4H_9)_3P$]$RuCl_2$	NH_4PF_6, CH_3OH, 65 °C, 4 h	43	1.8:1
8	(*p*-cymene)(Ph_3P)$RuCl_2$	- - -, CH_3OH, 65 °C, 6 h	4	1.9:1
9	(*p*-cymene)(Ph_3P)$RuCl_2$	$(C_2H_5)_3NHPF_6$, CH_3OH, 65 °C, 4.5 h	25	1.9:1
10	(*p*-cymene)(Ph_3P)$RuCl_2$	NH_4PF_6 + $AgOSO_2CF_3$, CH_3OH, 65 °C, 5.5 h	33	1.7:1
11	(*p*-cymene)(Ph_3P)$RuCl_2$	NH_4PF_6, C_2H_5OH, 78 °C, 4 h	27	3.3:1

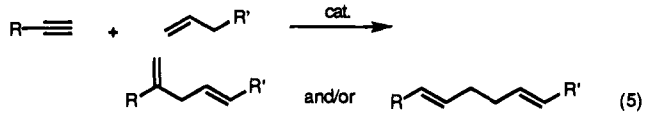
[a] All reactions were performed with 10 mol% catalyst at approximately 0.1 M in substrates. Reactions were monitored by gas chromatography. [b] Determined by NMR spectroscopy.

ketones (eq 4).[10] Based upon the ability of the ruthenium



(4)

catalysts to promote facile redox isomerization of allyl alcohols,[11,12] a ruthenium hydride intermediate as in path a is reasonable. Alternatively, prior coordination of both reactants as in path b may account for the catalytic effect. As a result of our investigations of this reaction, we discovered that the presence of an allylic hydroxyl group is not required as the above mechanisms suggest.[13] In this paper, we present a full account of the development of an effective cross coupling of acetylenes with simple olefins as outlined in eq 5.



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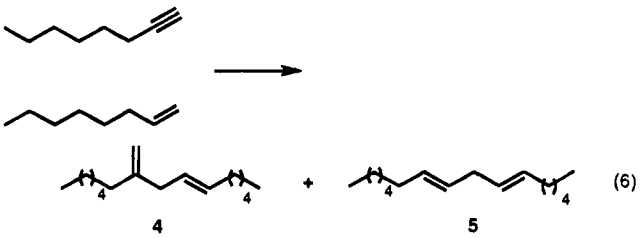
Catalyst. Studies of the addition of acetylenes to allyl alcohols (eq 4) explored the use of various ruthenium complexes including Cp*$RuCl_2$, $RuCl_3$, and $C_6H_6RuCl_2$ in addition to complex **3**.[14] While all catalyzed the reaction, complex **3** gave the best conversion. Alcohol solvents, notably methanol and ethanol, and aqueous mixtures, notably 1:1 to 3:1 DMF−water, gave the best conversions and selectivities. Extending these studies to the reaction of 1-octyne with 1-octene (eq 6) focussed on the use of the readily available arene ruthenium complexes[15] as summarized in Table 1. Several points are noteworthy.



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4 **5**

Addition of triphenylphosphine to cleave the dimeric arene complexes to monomers increases their catalytic effectiveness (entries 2 vs 6 and 3 vs 5). Whereas use of complex **3** preferentially does not employ ammonium hexafluorophosphate as a promoter, the arene complexes require its use (entry 6 vs 8). Further, decreasing the acidity of the promoter (entry 6 vs 9) decreases the yield. The nature of the aryl ring makes little difference. The slightly higher yields observed with the *p*-cymene complex (entry 6 vs entries 4 and 5) may result from its purity since it crystallizes more readily than the other arene complexes. Increasing the donor property of the phosphine (entry 6 vs 7) has only a small effect. Thus, the electronic properties of the ligands show little effect in contrast to the reconstitutive addition (eq 3). Removing chloride ion also decreases the yield (entry 10). In all of these cases (entries 2−10), the regioisomeric ratio of products remained virtually unchanged. Only a change in solvent from methanol to the less polar ethanol caused a change in regioselectivity in the case of the arene complexes (entry 11). However, the best conditions at present in terms of yield and regioselectivity employ complex **3** in aqueous DMF.

Medium Effect. Our studies of the reaction of allyl alcohols and terminal acetylenes suggested a beneficial effect for the

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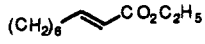
Table 2. Effect of Medium on Reaction of Methyl 10-Undecenoate and 2-Butyn-1-ol[a]

entry	solvent	additive[b]	temp	time	convsn[c] (%)	ratio[c] 6:7
1	3:1 DMF−H_2O		100 °C	2 h	60	2.5
2	3:1 DMF−H_2O	$(n\text{-}C_4H_9)_4NI$ (1 equiv)	100 °C	2 h	55	1.1
3	3:1 DMF−H_2O	$(n\text{-}C_4H_9)_4NCl$ (2 equiv)	100 °C	3 h	60	1.8
4	3:1 DMF−H_2O	AgOAc (1 equiv)	100 °C	2 h	55	1.8
5	CH_3OH		reflux	3 h	45	1.8
6	CH_3OH	$AgOSO_2CF_3$ (1 equiv)	reflux	3 h	40	1.2
7	CH_3OH	$(n\text{-}C_4H_9)_4NCl$ (1 equiv)	reflux	3 h	45	1.8
8	CH_3OH	$(n\text{-}C_4H_9)_4NCl$ (2 equiv)	reflux	3 h	60	1.7
9	CH_3OH	$(n\text{-}C_4H_9)_4NCl$ (10 equiv)	reflux	3 h	40	1.9
10	CH_3OH	PhCN (1 equiv)	reflux	3 h	30	1.6
11	CH_3OH	$(o\text{-anisyl})_3P$ (1 equiv)	reflux	3 h	8	1.5
12	CH_2Cl_2	$AgOSO_2CF_3$ (1 equiv)	rt	24 h	0	

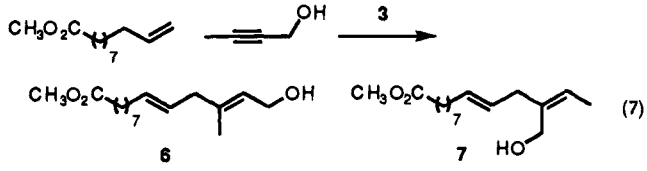
[a] All reactions performed with 5 mol% of complex **3** at approximately 0.1 M in both substrates. [b] The number of equivalents of additive is with respect to the catalyst. [c] Determined by gas chromatography which was also employed to monitor the reactions. Conversion determined by the relative percentage of methyl 10-undecenoate to all products at the stated reaction time.

Table 3. Chemoselectivity[a]

entry	R	R′	solvent	conversion[c]	product[e]	isolated yield %[f]	ratio[c] branched:linear
1	$n\text{-}C_3H_7$	$n\text{-}C_4H_9$	4:1 DMF−H_2O	80	**8a**	56(69)	5.2:1
2	$n\text{-}C_3H_7$	CH_2CH_2OH	1:1 DMF-H_2O	95	**8b**	57(60)	4.0:1
3	$n\text{-}C_3H_7$	$COCH_3$	1:1 DMF-H_2O	100[d]	**8c**	50(−)	3.8:1
4	$n\text{-}C_3H_7$	$CH_2CH_2CH_2CO_2CH_3$	1:1 DMF-H_2O	95	**8d**	71(75)	3.8:1
5	$n\text{-}C_3H_7$	$CH_2CH_2CH{=}CH_2$	CH_3OH[b]	99	**8e**	52(−)	6.4:1
6	$C_2H_5O_2C$	$n\text{-}C_4H_9$	3:1 DMF-H_2O	100	**8f**	90(−)	5.6:1
7	$TBDMSOCH_2$	$n\text{-}C_4H_9$	3:1 DMF-H_2O	100	**8g**	86(−)	5.0:1
8		$n\text{-}C_4H_9$	3:1 DMF-H_2O	100	**8h**	85(−)	1.7:1
9	$C_2H_5O_2C$		3:1 DMF-H_2O	65	**8i**	46(70)	5.3:1

[a] All reactions were performed with 5 mol% **3** at 100 °C for 2 h unless otherwise stated. [b] Reaction performed at the reflux temperature of methanol. [c] Determined by gas chromatography. [d] Reaction performed for 16 h. [e] Major regioisomer. [f] Numbers in parentheses represent isolated yields based upon unreacted starting material.

presence of a propargylic hydroxyl group or its corresponding MOM ether which we attributed to a coordinating effect to an otherwise highly coordinatively unsaturated ruthenium. We therefore chose to probe the effect of solvent on the reaction of methyl 10-undecenoate with 2-butyn-1-ol (eq 7) which might interact with this complexation and be revealed by a change in



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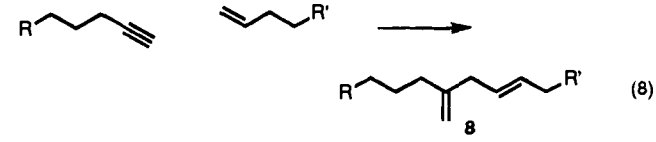
regioselectivity. Using 5 mol% of complex **3** in the stated solvent at reflux or 100 °C whichever was lower for reaction times normally of 2−3 h gave the results summarized in Table 2. Additives have a noticeable effect on the reaction in terms of both yield and regioselectivity in methanol and somewhat less in aqueous DMF. In the latter solvent, the presence of extra coordinating ions (entries 2 and 3) had little effect on conversion but decreased the regioselectivity with iodide exhibiting the most severe effect (entry 2). In methanol, increased concentration of chloride ion increased the conversion (entries 7 and 8), but a large excess of chloride relative to ruthenium became deleterious (entry 9). Since dissociation of chloride to form a cationic catalyst is envisioned to speed up the reaction, the presence of a large excess which would shift such an equilibrium to the neutral complex is expected to be deleterious. Weakly coordinating ligands like benzonitrile (entry 10) and more strongly coordinating ligands like tri-*o*-anisylphosphine (entry 11) dramatically slow reaction. Except for entries 1, 2, and 6, the regioselectivity was remarkably constant. While the source of the effect of iodide may be rationalized as a competition with the propargylic hydroxyl group for coordination to ruthenium, the silver triflate effect in methanol is not readily apparent. To discern whether the absence of a coordinating counterion may lead to some special effect of methanol which may directly interact with ruthenium, we explored the reaction in methylene chloride which cannot but to no avail since no conversion was observed. In summary, whereas methanol in the presence of external tetra-*n*-butylammonium chloride gives as high a yield as aqueous DMF, the latter gives the best regioselectivity and has been adopted as the solvent of choice.

Selectivity. The reaction exhibits extremely high chemoselectivity and control of olefin geometry. As illustrated in eq 8 and Table 3, placing functional groups including free hydroxyl groups, TBDMS ethers, ketones, and esters in either the alkene or alkyne has no deleterious effects. The reaction of 1,7-



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octadiene (entry 5) proved most interesting. Not only can monoaddition dominate over diaddition but also the regioselectivity was the highest for this substrate, even better than the saturated chain analogue (entry 1), a point we will return to in the discussion. An extraordinary example of the chemoselectivity is shown in entry 9 wherein the normally more reactive conjugated double bond is completely inert relative to the monosubstituted alkene.

Introducing branching at the propargylic position has a significant effect on regioselectivity wherein the reaction exhibits an increasing propensity to form the linear product (Table 3, entry 8). Replacing an alkyl branch by an oxygen inverts the regioselectivity to favor the linear product as summarized in

Table 4. Reaction of Progargylic Ethers and Analogues with Terminal Alkenes[a]

entry	R^1	R^2	R^3	R^4	solvent ratio DMF−H_2O	conversion[c]	product[d]	isolated[e] yield	ratio[c] branched:linear
1	n-C_5H_{11}	H	$PhCH_2$	CH_3	3:1	65	**9a**	53(82)	1:2.0
2	n-C_5H_{11}	H	TBDMS	CH_3	3:1	100	**9b**	88(- -)	1:2.4
3	n-C_5H_{11}	H	TIPS	CH_3	3:1	60[b]	**9c**	41(68)	1:3.7
4	$-(CH_2)_5-$		H	CH_3	3:1	85	**9d**	65(76)	1:9.9
5	CH_3		$-O(CH_2)_3O-$	CH_3	3:1	60	**10a**	41(68)	1:5.6
6	CH_3		$-O(CH_2)_3O-$	CO_2CH_3	1:1	90	**10b**	59(65)	1:5.6

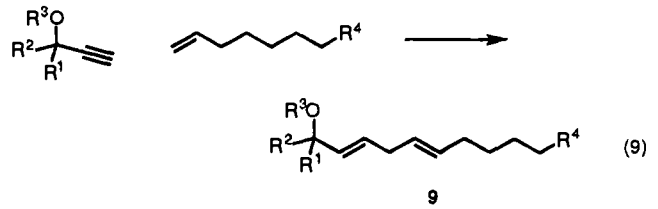
[a] All reactions were performed with 5 mol% **3** at 100 °C for 2 h unless stated otherwise. [b] Reaction time = 16 h. [c] Determined by gas chromatography. [d] Major regioisomer. [e] Numbers in parentheses represent isolated yields based upon unreacted starting material.

Table 5. Additions to Disubstituted Acetylenes

entry	R^1	R^2	R^3	R^4	solvent	product	isolated yield	ratio **12:13**
1	CH_3	n-C_4H_9	n-C_3H_9	H	3:1 DMF, H_2O	**12a**	65(86)	
2	CH_3	CH_3O_2C	H	H	CH_3OH	**12b, 13b**	54(64)	1
3	CH_3	CH_3	OH	H	3:1 DMF, H_2O	**12c, 13c**	24	2.6
4	$CH_3O_2C(CH_2)_3$	CH_3	OH	H	3:1 DMF, H_2O	**6,7**	38	2.6
5	$CH_3O_2C(CH_2)_3$	CH_3	OH	H	CH_3OH	**6,7**	39	1.8
6	$CH_3O_2C(CH_2)_3$	CH_3	OMOM	H	CH_3OH	**12d,13d**	45	1.7
7	$CH_3O_2C(CH_2)_3$	n-C_5H_{11}	OMOM	H	CH_3OH	**12e,13e**	54	1.8
8	$CH_3O_2C(CH_2)_3$	n-C_5H_{11}	OH	C_3H_7	CH_3OH	**12f,13f**[a]	46	2.9
9	$CH_3O_2C(CH_2)_3$	n-C_5H_{11}	OMOM	C_3H_7	CH_3OH	**12g,13g**	49	3.2

[a] Isolated as the O-methyl ether.

eq 9 and Table 4. Comparison of entries 1−3 indicates an



(9)

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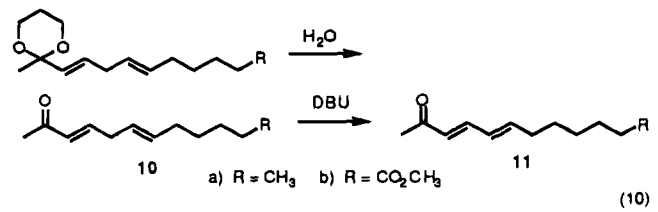
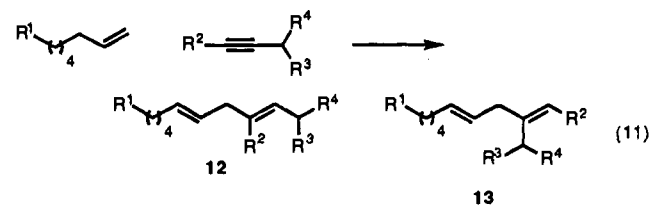
increase in linear product as the size of the oxygen substituent increases. Combining the oxygen effect with additional branching as in entry 4 gave the highest regioselectivity. Good regioselectivity is also observed in the case of a propargylic ketal (entries 5 and 6). In these two cases, the isolated products corresponded to the ketones **10a** and **10b** resulting from hydrolysis of the presumed initial ketal (eq 10). In these cases, a small amount of the product where the δ,ϵ double bond moved into conjugation accompanied the addition. Exposure of the initial adducts to DBU completed the isomerizations to the conjugated dienes **11a** and **11b**.



10 a) R = CH_3 b) R = CO_2CH_3 **11**

(10)

Reactions of disubstituted acetylenes were also explored as summarized in Table 5 and eq 11. The reaction of a symmetrical acetylene (entry 1) proceeded well to give a single product. A NOE of 8% between the bis-allylic methylene group



(11)

12 **13**

at δ 2.65 and the vinyl proton of the trisubstituted double bond (δ 5.12) established the E geometry of this double bond. Obviously, the symmetry of the acetylene precludes the issue of regioselectivity, but the control of olefin geometry is also excellent. With unsymmetrical disubstituted acetylenes, significant amounts of both regioisomers resulted. The presence of a propargylic oxygen substituent induced formation of the new C−C bond to the acetylenic carbon distal to that substituent. Use of methanol gave lower regioselectivity (entries 4 and 5) as noted earlier. Normally, the MOM ether showed a slight enhancement in regioselectivity (entry 8 vs 9). The biggest effect appears to be steric with additional branching at the propargylic center bearing oxygen showing the highest regioselectivity (entries 8 and 9 vs 5 and 6).

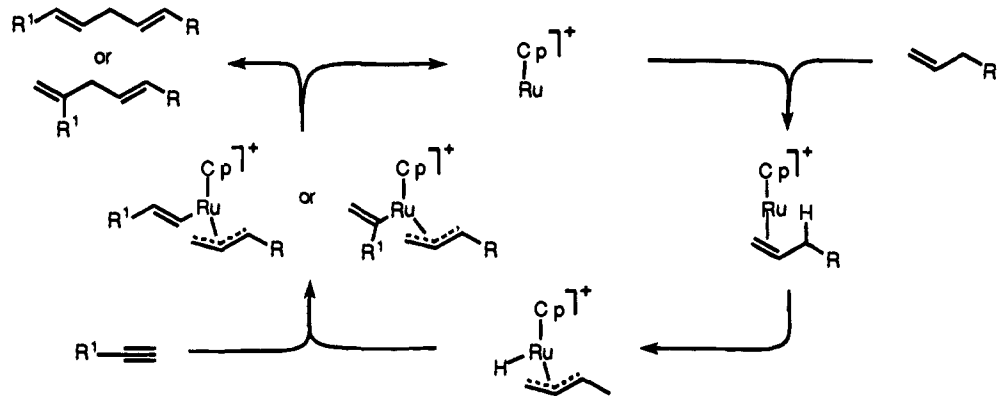
Discussion

This ruthenium catalyzed reaction of alkynes with terminal alkenes represents a practical method to achieve their addition without complications arising from self-condensation of either partner. How this process occurs is quite intriguing. First, an appropriate degree of coordinative unsaturation at ruthenium must be available. A polar medium allows ionization of the chloride to not only open a coordination site but also create positive charge to enhance kinetics. Further, we have shown that the COD is not simply displaced but reacts with the acetylene in a novel [2 + 2 + 2] fashion to open additional coordination sites.[16] Our initial thoughts centered on Scheme 1 in analogy to path a of eq 4 rather than the metallacycle mechanism of Scheme 2 due to the absence of homo-coupling products. It was reasoned that the formation of a ruthenacyclopentadiene which may lead to homo-coupling products derived from the alkyne partner should be preferred to that of a ruthenacyclopentene which is required to produce the cross-coupling products. However, we questioned the validity of Scheme 1 because the regioselectivity with respect to the alkene was disturbing in light of other work. In particular, the formation of a π-allylruthenium complex should undergo reductive elimination with formation of the new C−C bond to the more substituted allyl terminus.[6b,17] To probe the involvement of a π-allyl mechanism, we explored the reaction of (E)-

(16) Trost, B. M.; Imi, K.; Indolese, A. F. *J. Am. Chem. Soc.* **1993**, *115*, 8831.

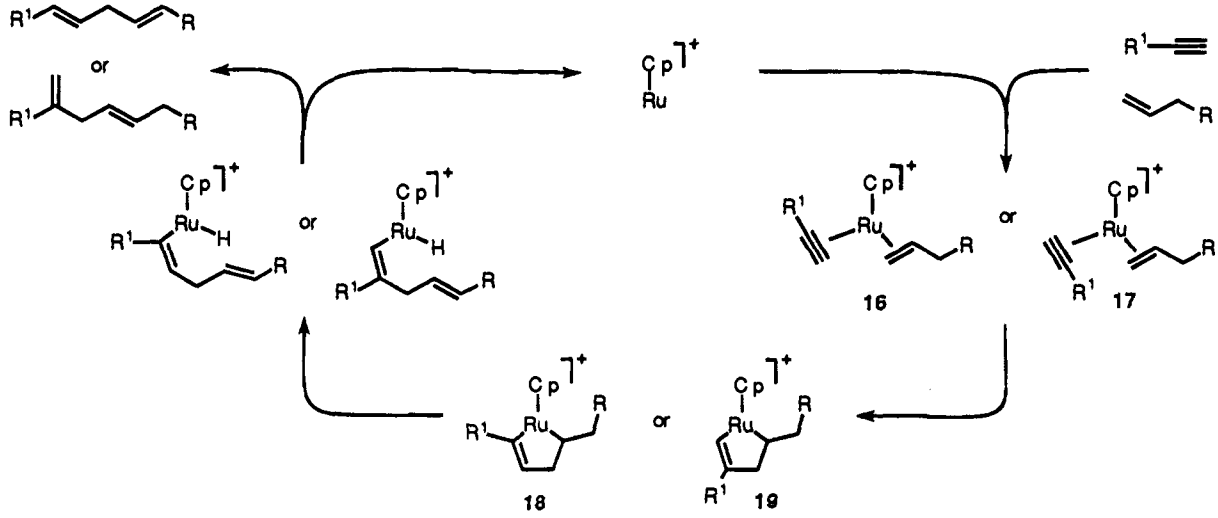
(17) Tsuji, Y.; Mukai, T.; Kondo, T.; Watanabe, Y. *J. Organomet. Chem.* **1989**, *369*, C51; Kondo, T.; Mukai, T.; Watanabe, Y. *J. Org. Chem.* **1991**, *56*, 487.

Scheme 1. Allyl Mechanism of Ru Catalyzed Addition[a]



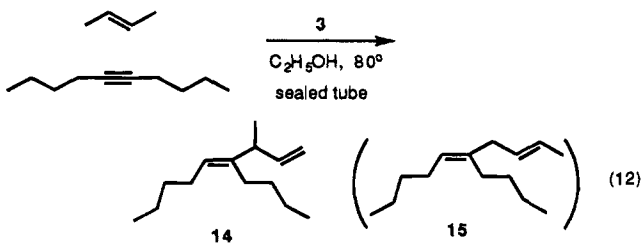
[a] Any open coordination site in these complexes would be anticipated to be occupied by some ligand present including possibly solvent.

Scheme 2. Ruthenacycle Mechanism of Addition[a]



[a] Any open coordination site in these complexes would be anticipated to be occupied by some ligand present including possibly solvent.

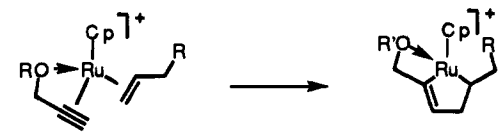
2-butene with 5-decyne which should give rise to the same regioisomer as a 1-alkene, i.e., formation of the new C−C bond to a methyl carbon of 2-butene if Scheme 1 operates. While internal alkenes react very much more slowly than terminal alkenes, the product was isolated in 23% yield. Spectral data clearly show the adduct is **14** and not the alternative **15**. While we cannot rigorously exclude the formation of different orientational isomers from the different precursors as the source of the differences, such an interpretation would not be in accord with other reactions involving π-allylruthenium chemistry.[6b,17] Thus, Scheme 1 was abandoned.



14 **15** (12)

This last experiment supports the ruthenacycle mechanism[18] of Scheme 2 which, furthermore, more consistently rationalizes the regioselectivity. Electronically, carbametalations normally prefer to attach the metal to the less substituted terminus of the alkyne which should favor **19**. However, steric effects between the two bonding carbons disfavor such a mode and consequently favor formation of **18**. The latter regioselectivity dominates in the cobalt catalyzed cyclooligomerizations.[19] Thus, in this case, electronic rather than steric effects dominate leading via **19** to the branched type products. On the other hand, as R′ increases in size, steric effects become more important, and **17** going to **19** should become disfavored relative to **16** going to **18**, exactly as observed.

This model may also explain some of the substituent effects observed. The presence of a propargylic oxygen substituent to favor bond formation to the distal acetylenic carbon may arise from the ability of the Ru to coordinate this substituent as in eq 13. The strain associated with this type of coordination in both complexes accounts for its relatively weak effect and its being supplanted by external ligands (e.g., iodide effect in Table 2).



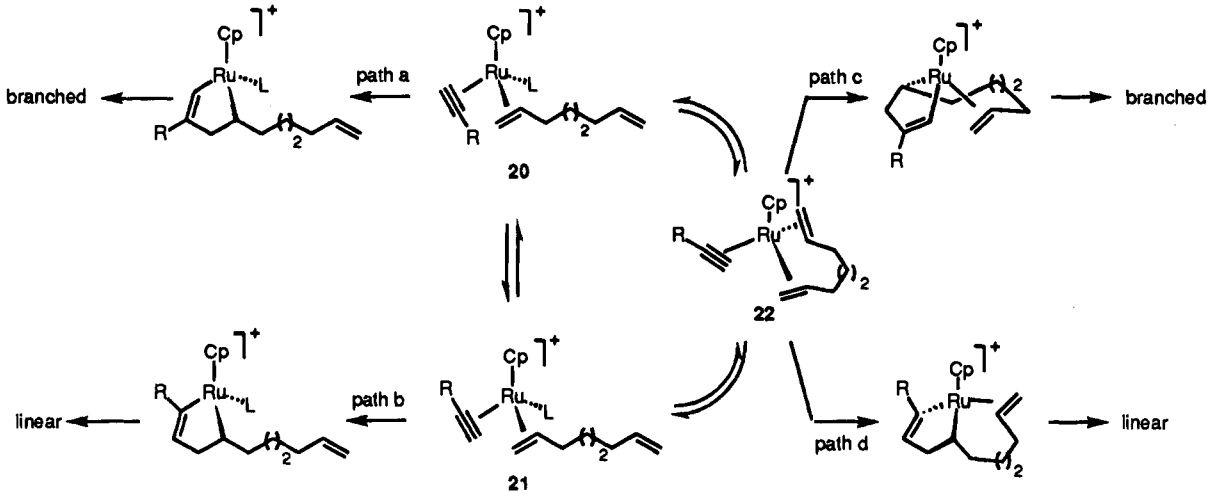
(13)

An analogous effect may account for the enhanced selectivity for branched product with 1,7-octadiene as outlined in Scheme

(18) For other reactions involving a ruthenacyclopentene intermediate, see: Mitsudo, T.; Kokuryo, K.; Shinsugi, T.; Nakagawa, Y.; Watanabe, Y.; Takegami, Y. *J. Org. Chem.* **1979**, *44*, 4492. Mitsudo, T.; Zhang, S.; Nagao, M.; Watanabe, Y. *J. Chem. Soc., Chem. Commun.* **1991**, 598. Trost, B. M.; Imi, K.; Indolese, A. F. *J. Am. Chem. Soc.* **1993**, *115*, 8831. Mitsudo, T.; Naruse, H.; Kondo, T.; Ozaki, Y.; Watanabe, Y. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 580.

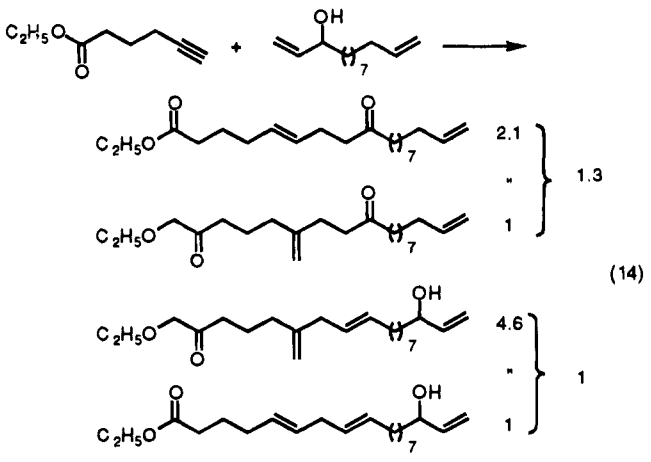
(19) Vollhardt, K. P. C. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 539.

Scheme 3



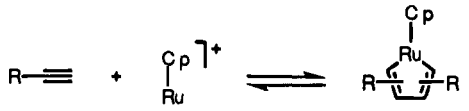
3. [Note that formation of the metallacycles by tautomerization of the coordinated alkene and alkyne formally raises the oxidation state of ruthenium and opens a coordination site. This event may be triggered by ligation.] If the reaction followed paths a and b exclusively, the branched to linear ratio should be the same as for 1-octene, which is not the case. On the other hand, if the second double bond occupies a coordination site by displacing L of **20** or **21** to form **22**, steric factors arising from interaction of R and the olefin that disfavor **20** relative to **21** are eliminated from consideration because of the symmetry of the bidentate coordination of the two double bonds. Thus, the bias for branched vs linear product may simply reflect the intrinsic steric and electronic factors associated with the tautomerization to the metallacycle (paths c and d) unperturbed by contributions of differential ground state interactions to the transition states for tautomerizations of **20** and **21**. The unique ability of a remote olefin relative to other substituents that might have been thought to be even stronger coordinators to be more effective in controlling regioselectivity supports this interpretation.

The presence of an open coordination site on ruthenium raises the question of whether an allyl alcohol is a better substrate than a simple alkene. To explore this question, both functionalities were incorporated in the same substrate to allow for an "internal" competition for the alkyne as illustrated in eq 14. While the analysis is complicated by the mixture of regioisomers obtained for each alkene, it is clear that the allyl alcohol is only slightly more reactive than a simple olefin. Thus, if the hydroxyl group of the allyl alcohol does coordinate (see eq 4), it offers only a modest kinetic enhancement. On the other hand, the presence of the allylic hydroxyl group has a significant effect on regioselectivity favoring the linear product, whereas the simple olefin leads to domination of the branched product.



(14)

The metallacycle mechanism raises the question as to why self-coupling of the acetylenes does not dominate. It would appear reasonable to expect a ruthenacyclopentadiene to form[20] which ultimately could lead to numerous products such as arenes by further reaction with the acetylene or cyclohexadienes by further reaction with the alkene. Neither of these two types of products is observed. One possible explanation invokes fast reversible formation of such a species as in eq 15. If the



(15)

ruthenacyclopentene and ruthenacyclopentadiene are in dynamic equilibrium, the products then depend upon the rate of the further reactions. The unimolecular β-hydrogen elimination which sets the stage for the Alder ene type product may then dominate over bimolecular paths for the further reactions of the ruthenacyclopentadiene. In support of this proposal is the effect of alkyne concentration on the rate of the reaction. Increasing alkyne concentration slowed the reaction. Thus, the reaction was typically performed at 0.1 M concentration. In the case of the reaction of 1-octyne with 3-buten-2-ol, a 10-fold excess of alkyne virtually stopped reaction. These results are in accord with the concept that the above equilibria are shifted in favor of the ruthenacyclopentadiene of eq 15 by excess alkyne.

This reaction provides an atom economical approach for selective C−C bond formation. Typically, a 1:1 ratio of reactants is employed. Its compatibility with most functional groups and its high control of olefin geometry are particularly noteworthy. Among the chemoselectivity issues, the catalyst discriminates against substituted alkenes therefore promoting highly chemoselective reaction with terminal alkenes. Further tuning of the steric demands of the catalyst is required to extend the reaction to more substituted alkenes.

The issue of regioselectivity can be managed by proper choice of reaction partners. Good selectivity for branched products occur with substrates lacking propargylic substituents. Employing α,ω-dienes further enhances this bias. On the other hand, reversal of regioselectivity to favor linear products occurs by introducing propargylic substituents. Thus, either regioisomeric product may be available.

(20) Cetini, G.; Gambino, O.; Sappa, E.; Valle, M. *J. Organomet. Chem.* **1969**, *17*, 437. Burt, R.; Cooke, M.; Green, M. *J. Chem. Soc. A* **1970**, 2981.

Table 6. Experimental Details for Table 3

entry	alkyne mg, mmol	olefin mg, mmol	Ru(COD)CpCl mg (μmol)	DMF [mL]	water [mL]	chromatography solvent, R_f	wt mg	yield (%)
1	22, 0.20	24, 0.21	3.2 (10)	1.5	0.5	hexane, 0.66	23	56
2	110, 1.00	140, 1.40	10.5 (34)	5	5	1:3 EtOAc:hexane, 0.32	115	57
3	225, 2.04	252, 2.56	10.6 (34)	10	10	1:8 EtOAc:hexane, 0.40	208	50
4	220, 2.00	453, 2.9	13.2 (43)	10	10	1:10 EtOAc:hexane, 0.37	370	71
5	225, 2.04	375, 3.41	15.3 (49)	methanol	10	hexane	229	52
6	84, 0.60	71, 0.63	7.6 (25)	4.5	1.5	1:10 EtOAc:hexane, 0.44	130	90
7	128, 0.60	71, 0.63	10.3 (33)	4.5	1.5	1:20 EtOAc:hexane, 0.56	159	86
8	43, 0.40	56, 0.50	6.0 (19)	3	1	hexane, 0.71	71	85
9	83, 0.59	107, 0.42	6.0 (19)	4.5	1.5	1:1 EtOAc:hexane, 0.25	72	46

Table 7. Experimental Details for Table 4

entry	Alkyne mg, mmol	Alkene mg, mmol	Ru(COD)CpCl mg (μmol)	DMF [mL]	water [mL]	chromatography solvent, R_f[a]	wt mg	yield (%)
1	111, 0.51	56, 0.50	8.0 (26)	4.5	1.5	1:20 EtOAc:hexane, 0.52	84	53
2	60, 0.25	56, 0.50	6.1 (20)	3	1	hexane, 0.37, 0.18	71	88
3	113, 0.4	71, 0.63	6.3 (20)	3	1	hexane, 0.65, 0.37	61	41
4	80, 0.64	67, 0.60	9.3 (30)	4.5	1.5	1:10 EtOAc:hexane, 0.38, 0.28	92	65
5	65, 0.51	57, 0.51	6.0 (19)	3	1	1:10 EtOAc:hexane, 0.42, 0.31	36	41
6	65, 0.51	66, 0.42	6.1 (20)	3	1	1:2 EtOAc:hexane, 0.41	56	59

[a] R_f of minor (branched) and major (linear) adducts when separated.

Overall, this reaction effects a series of bond changes that mirrors the Alder ene reaction. While the Alder ene reaction potentially possesses the necessary traits of selectivity and atom economy to classify it as an "ideal" reaction, its failure to achieve such status stems from the extreme conditions frequently required which diminish the selectivity and its limitations in scope. Hopefully, this new ruthenium catalyzed process, while mechanistically distinct from but structurally similar to the Alder ene reaction, will help make this reaction type approach its promise.

Experimental Section

Reactions were generally conducted under a positive pressure of dry nitrogen within glassware which had been flame-dried under a stream of dry nitrogen. Reaction flasks were sealed with red rubber septa and were, unless otherwise mentioned, magnetically stirred. Anhydrous solvents and reaction mixtures were transferred by oven-dried syringe or cannula. Flash chromatography employed E. Merck silica gel (Kiesselgel 60, 230−400 mesh). Analytical TLC was performed with 0.2 mm coated commercial silica gel plates (E. Merck, DC-Plastikfolien, Kieselgel 60 F_{254}). ^{1}H NMR spectra were obtained and recorded from Gemini GEM-200 (200 MHz), Nicolet NT-300 (300 MHz), or Varian XL-400 (400 MHz) instrument, with TMS as internal standard. ^{13}C NMR spectra were recorded on a Nicolet NT-300 (75 MHz) or a Varian XL-400 (100 MHz) instrument. Chemical shifts are reported in δ units, parts per million from the central peak of $CDCl_3$ (δ = 77.0) as an internal reference. IR spectra were performed by the NIH Mass Spectral Facility at the School of Pharmacy, University of California-San Francisco on a Kratos MS-90 instrument with an ionizing current of 98 mA and an ionizing voltage of 70 eV. Microanalyses were performed by M-H-W Laboratories, Phoenix, AZ.

Use of Arene Ruthenium Complexes. To 0.05 mmol of the arene ruthenium complex and 0.1 mmol of cocatalyst, if any, was added, in the following order, dry solvent, 83 mg (0.75 mmol) of 1-octyne, and 55 mg (0.50 mmol) of 1-octene. After heating at reflux for the indicated time, the solvent was evaporated, and the product was isolated by flash chromatography (pentane) to give the product. Ratios were established by integration of the signals for the vinyl protons in the NMR spectra. A table showing the experimental details appears in the supplementary material.

Medium Effect on Reaction of Methyl 10-Undecenoate and 2-Butyn-1-ol. Sequentially, 15.8 mg (0.08 mmol) of methyl 10-undecenoate, 5.4 mg (0.08 mmol) of 2-butyn-1-ol, and the indicated amount of additive were added by syringe to 1.1 mg (3.6 mmol) of CpRuCODCl[8] under nitrogen. The degassed solvent (1 mL), i.e., methanol distilled under nitrogen, dichloromethane distilled under nitrogen, or a mixture of degassed DMF/water (1:1), was added by syringe to the reaction mixture. This mixture then was stirred vigorously and heated at reflux (methanol) or at 100 °C (DMF−H_2O) for 3 h. The cooled reaction mixture was diluted with 15 mL of ether and filtered through a short plug of silica gel. The clear filtrate was analyzed by GC. A table showing the experimental details for each run appears in the supplementary material.

Addition of Terminal Alkyne with Terminal Alkene of Tables 3 and 4. General Procedure. Degassed water (1 mL) and degassed DMF (3 mL) were added to CpRu(COD)Cl (6.1 mg, 0.02 mmol) under nitrogen. Olefin (0.42 mmol) and alkyne (0.40 mmol) were added by syringe. The mixture was vigorously stirred and heated to 100 °C for 2 h. The mixture was poured into saturated aqueous $NaHCO_3$ (50 mL). The aqueous layer was extracted twice with ether (30 mL), and the organic layer was washed twice with water (20 mL). The organic layer was dried ($MgSO_4$) and evaporated *in vacuo*. The residue was purified by chromatography on silica. Tables 6 and 7 summarize the experimental details for each run.

Typical Procedure. Degassed water (1.5 mL) and degassed DMF (4.5 mL) were added to CpRu(COD)Cl (7.6 mg, 25 μmol) under nitrogen. 1-Octene (71 mg, 0.63 mmol) and ethyl 5-hexynoate (84 mg, 0.60 mmol) were added by syringe. The yellow mixture was vigorously stirred and heated to 100 °C for 2 h. The mixture was poured into saturated aqueous $NaHCO_3$ (50 mL). The aqueous layer was extracted twice with ether (30 mL), and the organic layer was washed twice with water (20 mL). The organic layer was dried ($MgSO_4$) and evaporated *in vacuo*. The residue was purified by chromatography on silica to give 130 mg (86%) of a colorless oil (R_f 0.44; ethyl acetate/hexane 1:10).

Spectral Data for Products of Table 3. 8a: IR (neat); 1645, 1467, 1437, 1378 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.40−5.44 (m, 2H, ABX_2, J_{AB} = 15.2 Hz), 4.72 (s, 2H), 2.69 (d, J = 5.6 Hz, 2H), 1.98−2.03 (m, 4H), 1.25−1.39 (m, 14H), 0.89 (t, J = 6.7 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 150.19, 132.90, 128.33, 109.62, 39.84, 36.21, 32.78, 32.01, 31.62, 29.43, 29.30, 27.84, 22.84, 22.74, 14.26 (2); additional signals for 6,9-hexadecadiene δ 131.67, 129.17, 35.90, 32.82, 32.74, 29.09; HRMS calcd for $C_{16}H_{30}$ 222.2348, found 222.2349.

8b: IR (neat) 1645, 1467, 1458, 1378, 1058 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.45−5.48 (m, 2H), 4.72 (s, 2H), 3.67 (dd, J = 12.0, 6.5 Hz, 2H), 2.69 (d, J = 3.9 Hz, 2H), 2.10−2.12 (m, 2H), 1.97−2.10 (m, 2H), 1.59−1.68 (m, 3H), 1.28−1.43 (m, 8H), 0.89 (t, J = 6.7 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 149.88, 131.82, 129.18, 109.79, 62.79, 39.72, 36.23, 32.59, 32.00, 29.27, 29.04, 27.81, 22.82, 14.25. Anal. Calcd for $C_{12}H_{26}O$: C, 79.93; H, 12.47. Found: C, 80.01; H, 12.49.

8c: IR (neat) 2928, 2857, 1720, 1645, 1430, 1358, 1156, 1018 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.56−5.59 (m, 2H), 4.74 (s, 1H), 4.72 (s, 1H), 3.14−3.16 (m, 2H), 2.75 (d, J = 4.2 Hz, 2H), 2.16 (s, 3H), 2.00 (t, J = 7.6 Hz, 2H), 1.21−1.31 (m, 8H), 0.89 (t, J = 6.8 Hz, 3H);

^{13}C NMR (75 MHz, $CDCl_3$) δ 208.01, 149.19, 133.42, 124.07, 110.25, 47.87, 39.69, 36.25, 31.98, 29.57, 29.25, 27.78, 22.82, 14.25; additional signals for 4,7-tetradecadien-2-one δ 134.56, 132.66, 128.00, 122.99, 36.03, 32.86, 29.82, 29.49; HRMS calcd for $C_{14}H_{24}O$ 208.1827, found 208.1844.

8d: IR (neat) 1743, 1644, 1436, 1199, 1171, 1018, 970 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.41–5.43 (m, 2H), 4.72 (s, 2H), 3.67 (s, 3H), 2.68 (d, J = 4.1 Hz, 2H), 2.31 (t, J = 6.5 Hz, 2H), 1.97–2.04 (m, 4H), 1.61–1.66 (m, 2H), 1.28–1.42 (m, 10H), 0.89 (t, J = 6.7 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.92, 149.99, 132.05, 128.92, 109.73, 51.73, 39.76, 36.22, 34.17, 32.33, 32.00, 29.27, 29.17, 27.82, 24.64, 22.82, 14.25; additional signals for methyl 6,9-hexadecadienoate δ 130.28, 129.87, 35.83, 34.27, 33.77, 32.79, 32.06, 29.71, 29.12, 28.83, 28.76, 25.00. Anal. Calcd for $C_{17}H_{30}O_2$: C, 76.63; H, 11.36. Found: C, 76.44; H, 11.36.

8e: IR (neat) 1643, 1457, 1439, 969, 911, 891 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.75 (ddt, J = 17.0, 10.21, 6.8 Hz, 1H), 5.34–5.38 (m, 2H), 4.86–4.97 (m, 2H), 4.65 (d, J = 1.0 Hz, 2 H), 2.62 (d, J = 4.9 Hz, 2H), 1.90–2.10 (m, 6H), 1.30–1.44 (m, 3H), 1.21 (s, 6H), 0.82 (t, J = 7.3 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 150.08, 139.49, 132.37, 128.79, 114.93, 109.69, 39.81, 36.22, 33.45, 32.16, 32.00, 29.29, 28.95, 27.84, 22.38, 14.26; HRMS calcd for $C_{16}H_{28}$ 220.2191, found 220.2174.

8f: IR (neat) 1737, 1460, 1374, 1178, 1022 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.33–5.51 (m, 2H, ABX_2, J_{AB} = 15.3 Hz), 4.77 (s, 1H), 4.75 (s, 1H), 4.13 (q, J = 7.1 Hz, 2H), 2.68 (d, J = 7.0 Hz, 2H), 2.29 (t, J = 7.5 Hz, 2H), 2.02 (m, 4H), 1.68–1.82 (m, 2H), 1.23–1.36 (m, 6H), 1.28 (t, J = 7.1 Hz, 3H), 0.89 (t, J = 7.0 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 174.39, 148.67, 133.18, 127.99, 110.71, 60.51, 39.62, 35.40, 34.06, 32.71, 31.62, 29.38, 23.02, 22.71, 14.41, 14.22; additional signals for ethyl 5,8-tetradecadienoate δ 131.87, 130.49, 130.14, 128.85, 35.83, 33.93, 32.12, 24.90. Anal. Calcd for $C_{16}H_{28}O_2$: C, 76.13; H, 11.19. Found: C, 75.98; H, 10.93.

8g: IR (neat) 1474, 1463, 1255, 1104, 970, 890, 836, 775 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.41–5.43 (m, 2H), 4.73, (s, 2H), 3.60–3.64 (m, 2H), 2.68 (d, J = 5.4 Hz, 2H), 2.30 (q, J = 6.7 Hz, 4H), 1.48–1.59 (m, 4H), 1.27–1.36 (m, 6H), 0.86–0.90 (m, 12H), 0.05 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 149.82, 132.96, 128.24, 109.88, 63.45, 39.77, 35.90, 32.76, 32.58, 31.62, 29.42, 26.19 (3), 24.02, 22.73, 18.54, 14.24, −5.18 (2); additional signals for 1-(*tert*-butyldimethylsiloxy)-5,8-tetradecadiene δ 131.72, 131.36, 129.48, 129.10, 32.73, 32.53, 25.92; Anal. Calcd for $C_{16}H_{28}OSi$: C, 73.99; H, 12.43. Found: C, 73.89; H, 12.37.

8h: IR (neat) 2925, 2953, 1449, 969, 888 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.35–5.44 (m, 2H), 4.73 (s, 1H), 4.69 (d, J = 1.5 Hz, 1H), 2.71 (d, J = 5.3 Hz, 2H), 1.95–2.05 (m, 3H), 1.67–1.79 (m, 4H), 1.06–1.39 (m, 12H), 0.89 (t, J = 6.8 Hz, 3H); additional signals for 1-cyclohexyl-1,4-decadiene 2.66 (t, J = 5.0 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.30, 132.79, 128.70, 108.04, 44.20, 38.69, 32.75, 32.59 (2), 31.61, 27.02 (2), 26.66, 26.35, 22.76, 14.24; additional signals for 1-cyclohexyl-1,4-decadiene 137.62, 131.60, 129.29, 126.65, 40.93, 35.94, 33.43 (2), 32.80, 31.67, 29.45 (2), 26.47; HRMS calcd for $C_{16}H_{28}$ 220.2191, found 220.2178.

8i: IR (neat) 1735, 1722, 1655, 1446, 1369, 1309, 1266, 1180, 1044, 972 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.93 (dt, J = 15.6, 7.0 Hz, 1H), 5.77 (dt, J = 15.6, 1.5 Hz, 1H), 5.34–5.41 (m, 2H), 4.72 (s, 1H), 4.70 (s, 1H), 4.14 (q, J = 7.1 Hz, 2H), 4.09 (q, J = 7.2 Hz, 2H), 2.64 (d, J = 5.9 Hz, 2H), 2.25 (t, J = 7.5 Hz, 2H), 2.15 (qd, J = 7.1, 1.4 Hz, 2H), 1.93–2.03 (m, 4H), 1.67–1.75 (m, 2H), 1.36–1.43 (m, 2H), 1.19–1.30 (m, 14H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.42, 167.52, 150.14, 148.64, 133.05, 128.07, 121.76, 110.73, 60.54, 39.59, 35.40, 34.04, 32.71, 32.42, 29.65, 29.45, 29.33, 29.24, 28.21, 22.99, 16.45, 14.43 (2); additional signals for diethyl 1,10,13-heptadecatrien-1,17-dicarboxylate 131.74, 130.43, 130.17, 128.96, 35.84, 33.92, 32.77, 32.12, 24.89; HRMS calcd for $C_{23}H_{38}O_4$ 378.2770, found 378.2784.

Spectral Data for Products of Table 4. 9a: IR (neat) 1455, 1092, 1070, 971, 732, 670 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.25–7.34 (m, 5H), 5.61 (dt, J = 15.7, 6.5 Hz, 1H), 5.41–5.47 (m, 2H), 5.35 (ddt, J = 15.7, 8.1, 1.2 Hz, 1H), 4.58 (d, J = 11.9 Hz, 1H), 4.35 (d, J = 11.9 Hz, 1H), 3.65–3.78 (m, 1H), 2.75 (t, J = 6.2 Hz, 2H), 2.02 (quin, J = 6.1 Hz, 2H), 1.57–1.99 (m, 2H), 1.26–1.48 (m, 12H), 0.85–0.91 (m, 6H); additional signals for 6-benzyloxy-7-methylene-9-pentadecene δ 5.01 (s, 1H), 4.98 (d, J = 1.6 Hz, 1H), 4.41 (d, J = 11.9 Hz, 1H), 4.25 (d, J = 11.9 Hz, 1H), 2.69 (d, J = 5.9 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 139.31, 132.63, 131.94, 131.63, 128.42 (2), 127.96, 127.90 (2), 127.50, 80.07, 69.64, 35.58, 35.07, 32.35, 31.59, 31.20, 29.00, 24.96, 22.41, 22.32, 13.81 (2); additional signals for 6-(benzyloxy)-7-methylene-9-pentadecene δ 148.57, 139.13, 132.93, 127.44, 112.95, 83.03, 69.93, 33.93, 33.36, 31.55, 21.24, 25.35; HRMS calcd for $C_{18}H_{25}O$ ($M^+ - C_5H_{11}$) 257.1987, found 257.1924.

9b: IR (neat) 1463, 1255, 1078, 969, 836, 775 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.52 (dt, J = 15.9, 6.2 Hz, 1H), 5.39–5.43 (m, 3H), 4.03 (q, J = 6.3 H, 1H), 2.69 (t, J = 5.3 H, 2H), 1.98 (q, J = 7.4 Hz, 2H), 1.23–1.44 (m, 14H), 0.86–0.89 (m, 15H), 0.04 (s, 3H), 0.02 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 134.95, 132.08, 129.15, 128.55, 74.12, 38.66, 35.38, 32.76, 32.04, 31.59, 29.43, 26.15 (3), 25.28, 22.85, 22.74, 18.46, 14.22 (2), −4.04, −4.62; HRMS calcd for $C_{22}H_{44}OSi$ 352.3161, found 352.3138.

6-(*tert*-Butyldimethylsiloxy)-7-methylene-9-pentadecene: IR (neat) 1463, 1255, 1082, 970, 836, 775 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.35–5.50 (m, 2H), 4.94 (q, J = 1.0 Hz, 1H), 4.77 (d, J = 1.6 Hz, 1H), 4.05 (t, J = 6.0 Hz, 1H), 2.76 (dd, J = 15.6, 5.5 Hz, 1H), 2.62 (dd, J = 15.6, 5.5 Hz, 1H), 2.01 (q, J = 6.4 Hz, 2H), 1.21–1.56 (m, 14H), 0.86–0.91 (m, 15H), 0.03 (s, 3H), 0.00 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 152.07, 133.03, 128.27, 110.47, 76.55, 36.72, 34.35, 32.76, 32.04, 31.64, 29.45, 26.08 (3), 25.40, 22.83, 22.74, 18.42, 14.23 (2), −4.51, −4.91; HRMS calcd for $C_{21}H_{41}OSi$ ($M^+ - CH_3$) 337.2922, found 337.2917.

9c: IR (neat) 1465, 1089, 1063, 970, 883, 680 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.33–5.50 (m, 4H), 4.11 (q, J = 6.4 Hz, 1H), 2.67 (t, J = 5.1 Hz, 2H), 1.95 (q, J = 6.2 Hz, 2H), 1.21–1.54 (m, 14H), 0.97–1.07 (m, 21H), 0.86 and 0.85 (2 × d, J = 6.7 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 135.01, 132.09, 129.29, 128.49, 74.32, 38.92, 35.42, 32.79, 32.17, 31.62, 29.43, 24.90, 22.88, 22.76, 18.34 (3), 18.30 (3), 14.24 (2), 12.57 (3); HRMS calcd for $C_{22}H_{43}OSi$ ($M^+ - C_3H_7$) 351.3059, found 351.3069.

6-(Triisopropylsiloxy)-7-methylene-9-pentadecene: IR (neat) 2931, 2867, 1465, 1089, 1063, 883, 680 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.32–5.48 (m, 2H), 4.90 (d, J = 1.8 Hz, 1H), 4.77 (d, J = 1.8 Hz, 1H), 4.18 (t, J = 6.2 Hz, 1H), 2.77 (dd, J = 16.5, 5.0 Hz, 1H), 2.58 (dd, J = 16.5, 5.0 Hz, 1H), 1.98 (q, J = 7.4 Hz, 2H), 1.51 (q, J = 7.1 Hz, 2H), 1.11–1.38 (m, 12H), 0.94–1.08 (m, 21H), 0.82–0.88 (m, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 151.21, 133.07, 128.23, 111.06, 76.82, 36.22, 33.82, 32.79, 32.18, 31.66, 29.47, 24.62, 22.86, 22.76, 18.30 (6), 14.25 (2), 12.55 (3); HRMS calcd for $C_{22}H_{43}OSi$ ($M^+ - C_3H_7$) 351.3059, found 351.3091.

9d: IR (neat) 3373, 2927, 2856, 1448, 971 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.67 (dt, J = 15.6, 5.9 Hz, 1H), 5.57 (d, J = 15.6 Hz, 1H), 5.33–5.49 (m, 2H), 2.72 (t, J = 5.1 Hz, 2H), 1.98 (q, J = 6.0 Hz, 2H), 1.45–1.67 (m, 9H); 1.24–1.42 (m, 8H), 0.89 (t, J = 6.8 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 137.76, 131.19, 127.47, 126.22, 70.86, 37.62 (2), 34.89, 32.10, 30.97, 28.74, 25.16, 22.11, 21.80 (2), 13.64; HRMS calcd for $C_{16}H_{28}O$ 236.2140, found 236.2137.

10a: IR (neat) 1676, 1627, 1361, 1254, 978 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.81 (t, J = 16.0, 6.5 Hz, 1H), 6.08 (dt, J = 16.0, 1.5 Hz, 1H), 5.52 (dt, J = 15.4, 6.4 Hz, 1H), 5.40 (dt, J = 15.4, 6.3 Hz, 1H), 2.91 (t, J = 6.3 Hz, 2H), 2.26 (s, 3H), 2.20 (q, J = 6.7 Hz, 2H), 1.24–1.41 (m, 6H), 0.89 (t, J = 6.8 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 199.54, 147.45, 134.53, 132.01, 125.44, 35.58, 32.76, 31.61, 29.20, 27.06, 22.70, 14.21.

10b: IR (neat) 1739, 1675, 1436, 1362, 1255, 1174, 977 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.80 (dtd, J = 16.0, 6.5, 1 Hz, 1H), 6.07 (dq, J = 16.0, 1.4 Hz, 1H), 5.39–5.54 (m, 2H), 3.67 (s, 3H), 2.92 (t, J = 6.2 Hz, 2H), 2.32 (td, J = 7.5, 1.0 Hz, 2H), 2.26 (d, J = 1.2 Hz, 3H), 2.05 (q, J = 7.0 Hz, 2H), 1.64 (q, J = 7.6 Hz, 2H), 1.40 (quin, J = 7.5 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 199.52, 174.85, 147.23, 133.69, 132.06, 126.06, 51.78, 35.53, 34.10, 32.37, 28.92, 28.86, 24.60; HRMS calcd for $C_{13}H_{20}O_3$ 224.1412, found 224.1429.

Reactions with Disubstituted Acetylenes. General Procedure. Alkene (0.50 mmol) and alkyne (0.50 mmol) were added by syringe to 7.5 mg (25 mmol) of CpRu(COD)Cl under nitrogen. Degassed methanol or 3:1 DMF–water was added by syringe. The reaction mixture then was heated to reflux for 3 h. The cooled reaction mixture was diluted with 15 mL of ether and filtered through a short plug of silica gel. The clear filtrate was analyzed by GC. The solution was

Table 8. Experimental Details for Table 5

entry	alkyne mg, mmol	alkene mg, mmol	CpRu(COD)Cl mg (μmol)	solvent (mL)	chromatography solvent, R_f	wt mg	yield[a] (%)
1	55, 0.40	56, 0.50	6.1 (10)	3:1 DMF–H_2O (4)	hexane, 0.78	62	65 (86)
2	64, 0.65	67, 0.60	10.0 (32)	CH_3OH (6)	1:10 ether:pentene, 0.52	68	54 (64)
3	35, 0.50	56.6, 0.50	7.8 (25)	3:1 DMF–H_2O (4)	1:3 EtOAc;hexane, 0.44	21.4	24
4	34, 0.49	97.3, 0.49	7.6 (25)	3:1 DMF–H_2O (4)	1:2 EtOAc:hexane, 0.54	29.2	38
5	35.5, 0.51	100.6, 0.51	7.8 (25)	CH_3OH (4)	1:2 EtOAc:hexane, 0.54	53.6	39
6	58.2, 0.51	99.9, 0.50	7.7 (25)	CH_3OH (2)	1:16 EtOAc:hexane, 0.18	70.3	45
7	64.0, 0.51	99.7, 0.50	7.7 (25)	CH_3OH (2)	1:16 EtOAc:hexane, 0.09	24	15
8	86.3, 0.51	99.6, 0.50	7.7 (25)	CH_3OH (2)	1:16 EtOAc:hexane, 0.28	100.3	54
9	42.5, 0.25	50.6, 0.26	4.0 (13)	CH_3OH (2)	1:16 EtOAc:hexane, 0.18	42.1	46
10	57.4, 0.25	49.8, 0.25	3.8 (12)	CH_3OH (2)	1:16 EtOAc:hexane, 0.20	50.6	49

[a] Yield in parentheses based upon recovered starting material.

evaporated *in vacuo*, and the residue was purified by chromatography on silica gel. The experimental details for each run are summarized in Table 8.

Spectral Data for Products of Table 5. 12a: IR (neat) 2957, 2925, 2858, 1466, 1459, 969 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.35–5.42 (m, 2H, ABX_2, J_{AB} = 15.2 Hz), 5.12 (t, J = 7.2 Hz, 1H), 2.65 (d, J = 6.1 Hz, 2H), 1.93–2.03 (m, 6H), 1.23–1.38 (m, 14H), 0.86–0.92 (m, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 138.81, 131.92, 128.88, 125.66, 40.26, 32.36, 32.18, 31.23, 30.40, 29.61, 29.09, 27.33, 22.61, 22.36, 22.25, 13.82 (3); HRMS calcd for $C_{18}H_{34}$ 250.2661, found 250.2660.

13b: IR (neat) 2926, 1722, 1648, 1436, 1171, 1147, 972 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.00 (q, t, J = 7.2, 1.2 Hz, 1H), 5.33–5.58 (m, 2H), 3.74 (s, 3H), 2.93 (dt, J = 5.2, 1.3 Hz, 2H), 1.96–2.04 (m, 2H), 1.97 (dt, J = 7.2, 1.3 Hz, 3H), 1.22–1.38 (m, 6H), 0.88 (t, J = 6.9 Hz, 3H); additional signals for **12b** δ 5.66–5.69 (m, 1H), 3.69 (s, 3H), 3.32 (d, J = 6.7 Hz, 2H), 1.86 (d, J = 1.3 Hz, 3H); HRMS calcd for $C_{13}H_{28}O_2$ 210.1620, found 210.1627.

12c: IR (neat) 3332, 1657, 1595, 1460, 1438, 1379, 1260, 1091, 1010, 970 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.44 (dt, J = 6.5, 15.4 Hz, 1H), 5.41 (t, J = 6.9 Hz, 1H), 5.34 (dt, J = 6.3, 15.4 Hz, 1H), 4.14 (d, J = 6.9 Hz, 2H), 2.66 (d, J = 6.3 Hz, 2H), 1.98 (dt, J = 6.6, 6.9 Hz, 2H), 1.64 (s, 3H), 1.22–1.36 (m, 6H), 0.86 (t, J = 6.8 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 132.77, 127.128, 123.62, 111.42, 59.39, 42.70, 32.47, 31.37, 29.31, 22.49, 16.22, 14.02; HRMS calcd for $C_{12}H_{22}O$ 182.1671, found 182.1677.

13c: IR (neat) 3407, 1610, 1460, 1400, 1379, 1259, 1080, 1025, 994, 971 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.53 (q, J = 6.8 Hz, 1H), 5.48 (dt, J = 6.1, 15.3 Hz, 1H), 5.39 (dt, J = 6.3, 15.2 Hz, 1H), 4.44 (s, 2H), 2.78 (d, J = 6.3 Hz, 2H), 1.98 (dt, J = 6.5, 6.9 Hz, 2H), 1.66 (d, J = 6.9 Hz, 3H), 1.20–1.36 (m, 6H), 0.86 (t, J = 6.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 138.00, 132.61, 128.04, 123.32, 60.06, 38.70, 32.45, 31.41, 29.18, 22.52, 15.27, 14.07; HRMS calcd for $C_{12}H_{22}O$ 182.1671, found 182.1672.

6: IR (neat) 3411, 1741, 1437, 1363, 1199, 1173, 1005, 969 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ 5.42 (dt, J = 6.1, 15.3, 1H), 5.36 (m, 1H), 5.33 (dt, J = 6.4, 15.3 Hz, 1H), 4.13 (d, J = 6.9 Hz, 2H), 3.64 (s, 3H), 2.65 (d, J = 6.0 Hz, 2H), 2.27 (t, J = 7.6 Hz, 2H), 1.97 (dt, J = 6.3, 6.7 Hz, 2H), 1.63 (s, 3H), 1.22–1.27 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.35, 139.04, 132.61, 127.23, 123.61, 59.38, 51.43, 42.65, 34.65, 34.05, 32.43, 29.30, 29.04, 28.85, 24.86, 16.27; HRMS calcd for $C_{16}H_{26}O_2$ ($M^+ - H_2O$) 250.1933, found 250.1934.

7: IR (neat) 3429, 1741, 1438, 1199, 1026, 993, 972 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.53 (q, J = 7.1 Hz, 1H), 5.46 (dt, J = 6.3, 15.3, 1H), 5.35 (dt, J = 6.5, 15.1 Hz, 1H), 4.13 (s, 2H), 3.64 (s, 3H), 2.77 (d, J = 6.0 Hz, 2H), 2.28 (t, J = 7.5 Hz, 2H), 1.97 (dt, J = 6.4, 6.5 Hz, 2H), 1.66 (d, J = 6.9, 3H), 1.23–1.27 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.36, 138.03, 132.43, 128.16, 123.31, 60.01, 51.45, 38.66, 34.08, 32.46, 29.37, 29.05, 28.91, 24.90, 13.19; HRMS calcd for $C_{16}H_{26}O_2$ ($M^+ - H_2O$) 250.1933, found 250.1922.

12d, 13d: IR (neat) 1742, 1675, 1437, 1378, 1363, 1242, 1198, 1171, 1149, 1103, 1046, 970, 921 cm^{-1}. **12d**: ^1H NMR (300 MHz, $CDCl_3$) δ 5.26–5.47 (m, J = 5.4, 5.8, 6.4, 7.1, 15.3 Hz, 3H), 4.02 (d, J = 6.9 Hz, 2H), 3.61 (s, 3H), 3.32 (s, 3H), 2.64 (d, J = 5.8 Hz, 2H), 2.25 (t, J = 7.5 Hz, 2H), 1.94 (dt, J = 6.3 Hz, 2H), 1.61 (s, 3H), 1.24 (br, 10H); additional signals for **13d** δ 3.99 (s, 2H), 3.33 (s, 3H), 2.71 (d, J = 5.6 Hz, 2H), 1.57 (d, J = 7.2 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.18, 140.18, 132.53, 127.19, 120.42, 95.45, 63.59, 55.06, 51.33, 42.66, 33.98, 32.39, 29.33, 29.29, 29.00, 28.85, 24.83, 16.28; additional signals for **13d** δ 135.18, 132.18, 127.66, 124.52, 95.41, 38.51, 18.21; HRMS calcd for $C_{17}H_{28}O_3$ ($M^+ - CH_3OH$) 280.2038, found 280.2044.

12e, 13e: IR (neat) 1742, 1670, 1464, 1437, 1378, 1361, 1246, 1199, 1171, 1149, 1103, 1044, 970, 921 cm^{-1}. **12e**: ^1H NMR (300 MHz, $CDCl_3$) δ 5.25–5.44 (m, 3H), 4.59 (s, 2H), 4.03 (d, J = 4.03 (d, J = 4.0 Hz, 2H), 3.62 (s, 3H), 2.61 (s, J = 5.8 Hz, 2H), 2.25 (t, J = 7.6 Hz, 2H), 2.01 (m, J = 6.0, 7.0 Hz, 2H), 1.95 (m, J = 6.6, 6.5 Hz, 2H), 1.57 (m, J = 7.1 Hz, 2H), 1.19–1.32 (m, 14H), 0.84 (t, 6.8 Hz, 3H); additional signals for **13e** δ 134.28, 132.13, 130.69, 127.81, 95.44, 63.93, 33.85, 31.41, 29.57, 27.62; HRMS calcd for $C_{22}H_{40}O_4$ 368.2927, found 368.2912.

12f, 13f: IR (neat) 1743, 1655, 1454, 1436, 1378, 1363, 1245, 1194, 1171, 1112, 1087, 969 cm^{-1}. **12f** ^1H NMR (300 MHz, $CDCl_3$) δ 5.21–5.47 (m, 3H), 4.95 (d, J = 5.3 Hz, 1H), 3.86 (dt, J = 6.2, 6.9 Hz, 1H), 3.64 (s, 3H), 3.20 (s, 3H), 2.67 (d, J = 6.0 Hz, 2H), 2.27 (t, J = 7.6 Hz, 2H), 1.93–2.03 (m, 4H), 1.51–1.59 (m, 2H), 1.22–1.39 (m, 18H), 0.83–0.90 (m, 6H); additional signals for **13f** δ 4.98 (d, J = 5.2 Hz, 1H), 3.83 (t, J = 6.7 Hz, 1H), 3.09 (s, 3H), 2.72, 2.74 (d, J = 5.8, 6.0 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.29, 143.12, 132.22, 128.03, 126.55, 76.74, 55.63, 51.42, 40.12, 38.07, 34.07, 32.46, 31.97, 30.42, 29.41, 29.09, 28.91, 28.07, 24.92, 22.51, 18.66, 14.17, 14.01; additional signals for **13f** δ 142.23, 131.79, 127.43, 126.40, 55.70, 36.58, 34.72, 33.88, 32.66, 32.32, 31.54, 27.53, 22.57, 14.06; HRMS calcd for $C_{23}H_{40}O_2$ ($M^+ - CH_3OH$) 348.3028, found 348.3020.

12g, 13g: IR (neat) 1743, 1656, 1456, 1437, 1378, 1244, 1198, 1156, 1097, 1039, 969, 936, 916 cm^{-1}. **12g**: ^1H NMR (300 MHz, $CDCl_3$) δ 5.25–5.44 (m, 2H), 4.95 (m, 1H), 4.62 (d, J = 6.6 Hz, 1H), 4.43 (d, J = 6.6 Hz, 1H), 4.25–4.32 (m, 1H), 3.63 (s, 3H), 3.32 (s, 3H), 2.65 (d, J = 5.8 Hz, 2H), 2.27 (t, J = 7.5 Hz, 2H), 1.92–2.29 (m, 4H), 1.54–1.61 (m, 2H), 1.26–1.37 (m, 18H), 0.89 (t, J = 7.1 Hz, 3H), 0.85 (t, J = 6.9 Hz, 3H); additional signals for **13g** δ 4.39, 4.51 (d, J = 6.6 Hz, 2H), 3.33 (s, 3H), 2.61 (m, J = 4.9 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.28, 143.56, 132.27, 127.92, 125.75, 93.02, 71.02, 55.15, 51.41, 40.09, 38.15, 34.06, 32.46, 31.90, 30.34, 29.40, 29.09, 28.91, 28.13, 24.92, 22.49, 18.82, 14.09, 13.99; additional signals for **13g** δ 143.11, 131.85, 130.42, 128.66, 72.77, 38.07, 35.84, 33.33, 31.97, 31.53, 30.42, 29.45, 28.07, 27.30, 19.21, 18.65; HRMS calcd for $C_{24}H_{42}O_3$ 378.3134, found 378.3148.

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Supplementary Material Available: Tables 9 and 10 and experimental details for eq 15 (3 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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